Low Temperature Fabrication for High Performance Flexible CsPbI$_2$Br Perovskite Solar Cells

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All-inorganic CsPbX$_3$-based perovskites, such as CsPbI$_2$Br, show much better thermal and illumination stability than their organic–inorganic hybrid counterparts. However, fabrication of high-quality CsPbI$_2$Br perovskite film normally requires annealing at a high temperature (>250 °C) that is not compatible with the plastic substrate. In this work, a Lewis base adduct-promoted growth process that makes it possible to fabricate high quality CsPbI$_2$Br perovskite films at low temperature is promoted. The mechanism is attributed to synthesized dimethyl sulfoxide (DMSO) adducts which allow a low activation energy route to form CsPbI$_2$Br perovskite films during the thermal annealing treatment. A power conversion efficiency (PCE) of 13.54% is achieved. As far as it is known, this is the highest efficiency for the CsPbI$_2$Br solar cells fabricated at low temperature (120 °C). In addition, the method enables fabrication of flexible CsPbI$_2$Br PSCs with PCE as high as 11.73%. Surprisingly, the bare devices without any encapsulation maintain 70% of their original PCEs after being stored in ambient air for 700 h. This work provides an approach for preparing other high performance CsPbX$_3$-based perovskite solar cells (PSCs) at low temperature, particularly for flexible ones.

Recently, all-inorganic cesium lead halide perovskites (CsPbX$_3$, X = I, Br, Cl, or mixed halides) have drawn extensive research efforts owing to their superior thermal and illumination stability compared to their organic–inorganic hybrid counterparts. The CsPbX$_3$-based inorganic perovskites have been demonstrated to be another promising and novel candidates for photovoltaic applications. However, most reported high performance CsPbX$_3$ perovskite solar cells (PSCs) need to be prepared at high temperature (>250 °C) to overcome the crystallization energy barrier for the black cubic perovskite phase(α-phase). Such high heating temperature will lead to a high fabrication cost and process complexity. Moreover, high temperature fabrication will limit the selection of substrates in the device and the possibility of application inflexible devices. When the CsPbX$_3$ perovskites are prepared at low temperature (≤150 °C), they generally exhibit a yellow orthorhombic phase (δ-phase) and poor crystallinity that are unsuitable for solar cell applications. Up to now, it is still challenging to fabricate pure α-phase CsPbI$_3$ perovskite films with high quality at low temperature, owing to a trade-off between processing temperature and device performance. Therefore, it is highly desirable to develop low temperature processed methods for preparing high quality CsPbI$_3$ inorganic perovskite films which can not only simplify the complicated device process, but also promote emerging flexible device technologies.

Among CsPbX$_3$-based perovskites, CsPbI$_2$Br is assumed to be a promising absorber layer for its balance of the trade-off between the bandgap and phase stability. In this scenario, recently, the CsPbI$_2$Br PSCs have been developed rapidly, which not only gave rise to a record power conversion efficiency (PCE) over 14%, but also exhibited good thermal and illuminated stability. However, it is still a serious challenge to synthesize pure α-phase CsPbI$_2$Br with superior photovoltaic performance at low temperature. Until now, there have been few reports on the preparation of CsPbI$_2$Br PSCs at low temperature. For example, Wang et al. applied HPbI$_3$ to replace PbI$_2$ as a precursor for preparing CsPbI$_2$Br film. It has been found that the precursor solution (CsI+PbBr$_2$+HPbI$_3$) can decrease the formation energy barrier for the α-CsPbI$_2$Br phase to help form...
a compact and pinhole-free film. The champion CsPbI$_2$Br PSC achieves a PCE of 10.56% and exhibits long-term phase stability at 130 °C. Lau et al. incorporated strontium into CsPbI$_2$Br to prepare PSCs at low temperature (100 °C). The champion CsPb$_{0.8}$Sr$_{0.2}$I$_2$Br PSCs delivered a highest PCE of 11.3% and better thermal stability. Most recently, Rao et al. controlled the morphology of CsPbI$_2$Br film by dimethyl sulfoxide (DMSO) solvent and obtain a pure α-phase CsPbI$_2$Br at low temperature (120 °C). The maximum efficiencies of the optimized rigid and flexible devices are only 10.4% and 7.3%, respectively. Therefore, up to now, the PCEs of rigid and flexible CsPbI$_2$Br PSCs prepared at low temperature (≤150 °C) are still lower than 12% and 8%, respectively.

In this work, we propose a low temperature scheme of DMSO-adduct promoted process (DAPP) for high quality perovskite films. The PbI$_2$(DMSO), PbBr$_2$(DMSO) adducts are obtained via treating lead halides with DMSO under low temperature conditions (60 °C), which can efficiently prevent rapid reaction of precursors and slow down the crystal growth. On the other hand, DMSO adducts can also reduce the formation energy of CsPbI$_2$Br perovskite that needs to be overcome by conventional precursors (PbI$_2$ and PbBr$_2$). By using the as-prepared DMSO adducts instead of commercial PbI$_2$ and PbBr$_2$ for the perovskite precursor solution, a high-quality perovskite film can be successfully prepared under low temperature conditions (120 °C), which is free of pinholes and impurities, and has high crystallinity and stability. Using the low temperature crystallized perovskite films, a high performance CsPbI$_2$Br PSC with PCE of 13.54% is fabricated (the current best CsPbI$_2$Br PSCs fabricated at low temperature (≤150 °C) have a PCE of <11%). In addition, the low temperature DAPP method enables the fabrication of flexible CsPbI$_2$Br PSCs with a high PCE of 11.73%. Furthermore, the flexible CsPbI$_2$Br PSCs are very stable, which can maintain 90% and 70% of their original PCEs after being bent under a curvature radius of 5 mm and stored in an ambient environment for 700 h, respectively. This work not only provides a novel route for preparing high-quality CsPbI$_2$Br perovskites at low temperature but also represents an important step for their application in high-performance and low-cost flexible electronics.

In thermodynamics, activation energy or formation energy represents the energy required for a chemical reaction. According to the recent literature, the reaction coordinate diagram of the all-inorganic perovskite material formation via different pathways is presented in Figure 1. In the conventional pathway based on pure PbI$_2$ and PbBr$_2$, the formation of all-inorganic perovskite materials needs to overcome a large energy barrier ($E_a$). Interestingly, it is found that the formation of all-inorganic perovskite materials undergoes two-stage reactions in a Lewis base adduct-promoted pathway, PbI$_2$(Lewis base)$_x$ formation and perovskite formation. The first step needs to overcome a small energy barrier ($E_{a1}$) from PbI$_2$ to PbI$_2$(Lewis base)$_x$, meaning that PbI$_2$(Lewis base)$_x$ can be obtained at low temperature for a short time. $E_{a2}$ is the Lewis base adduct-promoted pathway from PbI$_2$(Lewis base)$_x$ to perovskite, which is substantially lower than that of the conventional pathway ($E_a$). Therefore, a high-quality perovskite film can be readily obtained at low temperature for a short time through the Lewis base adduct-promoted growth.

Therefore, in order to obtain high quality inorganic perovskite materials at low temperature, in this work, we propose a DMSO adduct-promoted process (DAPP) for formation of all-inorganic perovskite CsPbI$_2$Br. The DAPP is a two-stage reaction pathway with a lower activation energy and different from the conventional single pathway with a higher activation energy. First, the DMSO adducts, PbI$_2$(DMSO), and PbBr$_2$(DMSO), are synthesized at 60 °C as precursors to replace PbI$_2$ and PbBr$_2$ in conventional all-inorganic perovskite solution. On the one hand, the DMSO adducts can effectively retard the fast reaction between PbI$_2$, PbBr$_2$, and CsI during the evaporation of solvent. On the other hand, the DMSO adducts can reduce the formation energy of CsPbI$_2$Br perovskite as discussed before.

The fabrication of PbI$_2$(DMSO) and PbBr$_2$(DMSO) adducts contains two steps, namely, I) adding toluene as a nonsolvent into PbI$_2$ or PbBr$_2$, solution dissolved in DMSO to obtain white precipitation and II) annealing the white precipitation at 60 °C for 24 h. The formation of DMSO adducts is confirmed by X-ray powder diffraction (XRD) (Figure S1a, Supporting Information) and ultraviolet–visible (UV–Vis) absorption spectra (Figures S2a,b, Supporting Information). The XRD patterns of the white precipitations are well matched with PbI$_2$(DMSO) and PbBr$_2$(DMSO) phase reported in literature. Compared with PbI$_2$ powders, the absorption edge of PbI$_2$(DMSO) precipitation is removed to short wavelength corresponding to the change from yellow-colored PbI$_2$ powered to colorless PbI$_2$(DMSO) adducts, which is in agreement with the reported results.

Then the CsPbI$_2$Br precursor films are deposited on the rigid substrate by coating precursor solution via antisolvent ways. To evaluate the influence of the DAPP on the crystallization process of CsPbI$_2$Br perovskite, the CsPbI$_2$Br precursor films without annealing are stored in a glove box for 24 h (Figure S3, Supporting Information). It is found...
that the CsPbI₂Br precursor film without DAPP turns black, indicating crystallization of CsPbI₂Br film. Conversely, the CsPbI₂Br precursor film with DAPP shows dark brown, meaning that the DAPP can slow down the crystallization process of CsPbI₂Br. In order to further confirm the influence of the DAPP, the CsPbI₂Br precursor films are annealed at low temperature (35 °C) for different times (Figure S4, Supporting Information), the CsPbI₂Br films without and with DAPP turn black and light brown after being annealed at 35 °C for 35 min, respectively. Therefore, it is concluded that the DAPP can control the crystallization kinetic of CsPbI₂Br perovskite, which is crucial for high quality CsPbI₂Br film.[21]

Figure 2a shows XRD patterns of CsPbI₂Br films without and with DAPP annealed at 65 or 120 °C for 10 min. Many studies have found that the cubic α-CsPbI₂Br phase is often obtained when the annealing temperature is higher than 250 °C.[22–24] In our work, it is interesting to find that a pure cubic α-CsPbI₂Br phase transition easily occurs by using DMSO adducts as precursor even at 65 °C for 10 min. The characteristic Bragg peaks of CsPbI₂Br thin films at 2θ = 14.6°, 29.5° show that both films are well-oriented in the cubic (100) direction. The peak splitting of the (100) and (200) planes is observed in the control film (Figure S5, Supporting Information) annealed at 65 °C for 10 min, indicating the separate growth of I-rich (2θ = 14.4°, 29.1°) crystals.[25] The XRD peak intensity of CsPbI₂Br films is enhanced after annealing at high temperature (120 °C), which benefits from the improved crystallinity of the CsPbI₂Br film. The intensity ratio of CsPbI₂Br films with and without DAPP is 1.2, which means that the quality of CsPbI₂Br films is improved after DAPP optimizing.

The UV–Vis absorption spectra of CsPbI₂Br films with and without DAPP are shown in Figure S6 (Supporting Information). The CsPbI₂Br film with DAPP exhibits an increased absorption over the entire absorption range compared to CsPbI₂Br film without DAPP, which is due to its higher crystallinity (Figure 2a). To investigate the influence of DAPP on photogenerated charge carriers in the CsPbI₂Br films, the steady-state photoluminescence (PL) and time-resolved PL (TRPL) measurements are performed (Figure S7, Supporting Information). The PL intensity of the CsPbI₂Br film with DAPP is much higher than that of the film without DAPP, suggesting a significantly reduced nonradiative recombination rate within the perovskite film. The PL decay lifetimes of the CsPbI₂Br films are determined by TRPL measurements (Figure S7b and Table S2, Supporting Information). The CsPbI₂Br film with DAPP shows a much longer lifetime (11.57 ns) than that of the film without DAPP (3.41 ns), indicating that the improved crystalline quality of CsPbI₂Br film can significantly prolong the lifetimes of carriers.[26]

Figure 2b shows the cross-sectional scanning electron microscopy (SEM) image of the completed CsPbI₂Br PSC on the rigid substrate. The device has a structure of (FTO/TiO₂/CsPbI₂Br/Spiro-OMeTAD/Au). The energy band levels of the CsPbI₂Br PSC are shown in Figure S8 (Supporting Information). In this device, the 300 nm CsPbI₂Br perovskite layer is prepared by PbI₂(DMSO), PbBr₂(DMSO) and CsI, which is free of pinholes and has a compact surface (Figure S9a, Supporting Information) that is critical for the photovoltaic performance.

Figure 2. a) XRD patterns of CsPbI₂Br films without and with DAPP annealed at 65 or 120 °C for 10 min. b) The cross-sectional view of the completed CsPbI₂Br PSCs with DAPP. c) J–V curve of the champion CsPbI₂Br PSC under one sun (AM 1.5G illumination). d) The corresponding external quantum efficiency (EQE) spectrum together with the integrated J_{SC} of the champion CsPbI₂Br PSC.
of CsPbI₂Br PSC. The DMSO in DMSO adducts, PbI₂(DMSO) and PbBr₂(DMSO), could not easily escape from the precursor film after spin-coating, which could enhance the mass transport and diffusion, slow down the rate of crystallization, and eventually improve the film quality.[26] In contrast, when the control solution without DMSO adducts is deposited onto the TiO₂ layer, some pinholes can be observed on the film probably due to the rapid crystallization (Figure S9b, Supporting Information), which could lead to the lower PCEs and instability for inorganic PSCs. This result indicates that high quality CsPbI₂Br perovskite film can be obtained by using DMSO adducts through a low temperature solution process. The representative current density–voltage (J–V) curve of the CsPbI₂Br PSCs is given in Figure 2c. The champion device achieved a VOC of 1.18 V, a FF of 77.23%, a JSC of 14.89 mA cm⁻², and a PCE as high as 13.54%, which is one of the highest PCEs among the all-inorganic perovskite PSCs to date and much higher than the PCEs of the reported all-inorganic perovskite PSCs prepared at low temperature (Table 1).[27–29] The device also shows a negligible J–V hysteresis (Figure S10, Supporting Information). Figure 2d shows the corresponding external quantum efficiency (EQE) of the CsPbI₂Br device with an integrated photocurrent density of 14.20 mA cm⁻², which is close to the JSC derived from the J–V measurement.

| Configuration                                      | Temperature [°C] | VOC [V]  | JSC [mA cm⁻²] | FF [%]  | PCE [%] | Ref. |
|----------------------------------------------------|-----------------|----------|---------------|---------|---------|------|
| FTO/TiO₂/CsPbI₂Br/spiro-OMeTAD/Au (rigid)          | 130             | 1.13     | 13.6          | 68.6    | 10.6    | [12] |
| FTO/TiO₂/CsPbI₂Br/P3HT/Au (rigid)                  | 100             | 0.96     | 13.4          | 59.8    | 7.7     | [13] |
| FTO/TiO₂/CsPb₁.₅Sr₀.₅I₂Br/P3HT/Au (rigid)          | 100             | 1.06     | 14.9          | 70.9    | 11.3    | [13] |
| ITO/NiOₓ/CsPbI₂Br/C₆₀/BCP/Ag (rigid)               | 120             | 1.05     | 12.6          | 78.7    | 10.4    | [14] |
| PET/ITO/NiOₓ/CsPbI₂Br/C₆₀/BCP/Ag (flexible)        | 120             | 0.97     | 11.5          | 65.0    | 7.3     | [14] |
| FTO/TiO₂/CsPbI₂Br/spiro-OMeTAD/Au (rigid)          | 120             | 1.18     | 14.9          | 77.2    | 13.5    | This work |
| PET/ITO/Nb₂O₅/CsPbI₂Br/spiro-OMeTAD/Au (flexible)  | 130             | 1.19     | 14.6          | 67.3    | 11.7    | This work |

PSCs are further fabricated by utilizing ITO/polyethylene terephthalate (PET) as the conductive transparent electrode/substrate. Nb₂O₅ film is e-beam evaporated at room temperature as an electron transport layer.[30] The SEM image of Nb₂O₅ film on flexible substrate is shown in Figure 3a. The Nb₂O₅ film has a thickness of 60 nm and shows a smooth surface morphology with uniform grain structure. As shown in Figures 3b,c, the CsPbI₂Br film on flexible substrate with DAPP has a dense and smooth surface, and passivated grain boundary. In contrast, the control CsPbI₂Br film without DAPP has a rough surface and some cracks, which is probably due to the rapid crystallization process.[25,31]

In order to investigate the effect of temperature on the crystallization of CsPbI₂Br films on the flexible substrates, the

Figure 3. a) SEM image of Nb₂O₅ film coated on flexible PET substrate. SEM images of the CsPbI₂Br perovskite films coated on PET/ITO/Nb₂O₅ substrate b) without and c) with DAPP. d) XRD patterns and e) the diffraction intensity and full width at half maxima (FWHM) of (100) peaks of CsPbI₂Br perovskite films with DAPP annealed at different temperatures.
CsPbI₂Br solution with DMSO adducts are spin-coated on Nb₂O₅/ITO/PET substrate and then annealed at different temperatures (100, 110, 120, 130, 140 °C) on a hotplate to form a 300 nm CsPbI₂Br perovskite film. The XRD results of CsPbI₂Br films are shown in Figure 3d,e, the pure CsPbI₂Br thin films show the Bragg peaks at 14.6° and 29.5°. As the annealing temperature increases, the intensities of the diffraction (100) peaks increase while the full width at half maxima (FWHM) decreases due to the increased crystallinity of perovskite film. However, with further increases of the temperature to 140 °C, the intensity of the diffraction peak decreases while the FWHM increases, which is probably due to the influence of thermal deformation behavior of PET substrates.[32] The effect of different annealing times on the crystallization of CsPbI₂Br films at the optimal annealing temperature is also investigated (Figure S11, Supporting Information). The intensities of (100) peak increase from 2 to 30 min due to the increased crystallinity of perovskite film. With further annealing up to 40 min, the change of the (100) peak intensity is not obvious.

To build up flexible CsPbI₂Br PSCs, as shown in Figure 4a, a conventional n-i-p architecture (PET/ITO/Nb₂O₅/CsPbI₂Br/spiro-OMeTAD/Au) is adopted. The energy band levels of the flexible CsPbI₂Br PSC are shown in Figure S12 (Supporting Information). The effect of different annealing times on the crystallization of CsPbI₂Br films at the optimal annealing temperature is also investigated (Figure S11, Supporting Information). The statistical distributions of the photovoltaic parameters are summarized in Table S1 and Figure S14 (Supporting Information), respectively. The optimized annealing time at 130 °C is 10 min. The J-V curve of the champion flexible CsPbI₂Br PSC annealed at optimized condition (130 °C-10 min) is shown in Figure 4b. The PCE of the flexible CsPbI₂Br PSC can reach up to 11.73% with a \( V_{OC} \) of 1.19 V, a FF of 67.25%, and a \( J_{SC} \) of 14.61 mA cm\(^{-2}\). In contrast, the control flexible CsPbI₂Br PSC without DAPP only exhibits a PCE of 9.48% with a \( V_{OC} \) of 1.08 V, a FF of 65.0% and a \( J_{SC} \) of 13.55 mA cm\(^{-2}\) (Figure S15, Supporting Information). Obviously, all the photovoltaic parameters of CsPbI₂Br PSCs with DAPP have higher values than the control samples. Compared

Table 2. Comparison of the performance parameters of the CsPbI₂Br PSCs with DAPP annealed at different temperatures.

| Conditions | \( V_{OC} \) [V] | \( J_{SC} \) [mA cm\(^{-2}\)] | FF [%] | PCE [%] |
|------------|-----------------|-----------------|--------|--------|
| 100 °C-10 min | 1.16 | 14.33 | 65.71 | 10.91 |
| 110 °C-10 min | 1.17 | 14.39 | 65.79 | 11.03 |
| 120 °C-10 min | 1.17 | 14.47 | 67.37 | 11.40 |
| 130 °C-10 min | 1.19 | 14.61 | 67.25 | 11.73 |
| 140 °C-10 min | 1.12 | 14.17 | 66.34 | 10.51 |
with the control device, the PCE of CsPbI$_2$Br PSCs with DAPP is increased about 24%. Figure 4c shows the corresponding EQE of the optimized flexible CsPbI$_2$Br device with an integrated $J_{SC}$ value of 14.28 mA cm$^{-2}$, which agrees well with the $J$–$V$ measurements. To confirm the reliability of the $J$–$V$ measurements, the current density and PCE at the maximum power point (0.94 V) are recorded as functions of time, as presented in Figure 4d. When measured for a period of light soaking times, a stabilized efficiency of 11.63% with a stable $J_{SC}$ of 12.37 mA cm$^{-2}$ is obtained, which is very close to the efficiency value obtained by the $J$–$V$ measurements.

To demonstrate the flexible property of CsPbI$_2$Br PSCs, the mechanical bending tests of flexible CsPbI$_2$Br PSCs are carried out with different curvature radii. The $J$–$V$ curves of the flexible devices before and after bending at curvature radii of 12, 7, and 5 mm for 300 cycles are shown in Figures 5a–c, respectively. A vernier caliper is applied to define the curvature radius.

The performance of the flexible CsPbI$_2$Br PSC exhibits no significant degradation after bending at a curvature radius of 12 mm for 300 cycles. In addition, the flexible CsPbI$_2$Br PSC retained more than 90% of its initial PCE value even after bending at a curvature radius of 5 mm for 300 cycles, proving excellent mechanical stability.

To examine the effect of the DAPP method upon the device air stability, CsPbI$_2$Br films and PSCs are stored without encapsulation at room temperature in ambient air at ≈30% relative humidity (RH). As shown in Figure 6a,b, CsPbI$_2$Br films annealed at 65 °C with and without DAPP undergo a complete degradation after storing in air for 4 h. When the annealing temperature is increased to 120 °C, CsPbI$_2$Br film without DAPP shows a significant degradation, whereas the CsPbI$_2$Br film with DAPP remains in its initial state, proving that DAPP method can enhance the stability of CsPbI$_2$Br film that annealed at low temperature. Figure 6c,d shows the long-term air stability of flexible CsPbI$_2$Br PSCs with or without DAPP, the flexible PSCs with

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**Figure 5.** $J$–$V$ curves of the flexible CsPbI$_2$Br PSCs before and after 300 bending cycles with the curvature radius of a) 12 mm, b) 7 mm, and c) 5 mm, respectively. The insets show the corresponding bending images.

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**Figure 6.** a) Comparison of the air stability (humidity: ≈30%) of the CsPbI$_2$Br perovskite films without and with DAPP annealed at different temperatures. The air stability (humidity: ≈30%) of the flexible CsPbI$_2$Br PSCs b) without and c) with DAPP for different time periods.
DAPP still retain ~70% of the initial efficiencies after 700 h aging in air. Such a long-term stability of flexible CsPbI₂Br PSCs is closely related to the high-quality of CsPbI₂Br film. In contrast, the efficiencies of the control device without DAPP rapidly decrease to less than 60% of their initial values within 5 h.

Meanwhile, the thermal (100 °C) or high-humidity (RH 55%, 25 °C) stabilities of flexible CsPbI₂Br PSCs with or without DAPP are also investigated, respectively (Figure S16, Supporting Information). It turns out that the CsPbI₂Br PSCs with DAPP have better thermal and humidity stabilities than their counterparts without DAPP. However, the stability performance of CsPbI₂Br PSCs is still inferior to the CsPbBr₃ and CsPbBr₂PSCs with the lower iodide content.37,38 Further enhancements in stability can be expected via reducing the content of iodide and/or replacing moisture sensitive Spiro-OMeTAD with dopant-free hole transporting materials.

In summary, we have demonstrated a low temperature DAPP method to fabricate high quality CsPbI₂Br film through reducing the reaction energy of precursors by using PbI₂(DMSO) and PbBr₂(DMSO) to replace PbI₂ and PbBr₂. This method can obtain a high quality and stable CsPbI₂Br film even at 120 °C. A CsPbI₂Br PSC with PCE of 13.54% is fabricated on rigid substrate, showing negligible hysteresis. In addition, the low temperature DAPP method based on DMSO adducts enables the fabrication of the flexible CsPbI₂Br PSCs with a highest reported PCE of 11.73%, the flexible CsPbI₂Br PSCs can maintain 90% and 70% of their original PCE after being bent under a curvature radius of 5 mm and stored in an ambient environment for 700 h, respectively. Therefore, this work not only proves the feasibility of producing highly efficient CsPbI₂Br PSCs on rigid substrates at low temperature, but also opens a new avenue to realize the high performance flexible CsPbI₂Br PSCs on flexible substrates.

**Experimental Section**

**Materials:** The PbI₂(DMSO), PbBr₂(DMSO) adducts were prepared by dissolving the appropriate amount of the commercial PbI₂ (99.99%, Alfar Aesar) and PbBr₂ (99.99%, Alfar Aesar) in DMSO with heating (60 °C) and stirring, respectively. Then 40 mL of anisole (toluene, acetone or isopropanol) was slowly added into the PbI₂ or PbBr₂ solution to precipitate the DMSO adducts. After the precipitation was completely produced, it was filtered and dried in a vacuum oven at 100 °C for 24 h to get white PbI₂(DMSO)₂ and PbBr₂(DMSO)₂ powders. The PbI₂(DMSO) and PbBr₂(DMSO) adducts were obtained by annealing PbI₂(DMSO)₂ and PbBr₂(DMSO)₂ in a vacuum oven at 60 °C for 24 h, respectively.

**Device Fabrication:** The rigid all-inorganic CsPbI₂Br PSCs were fabricated with a structure of FTO/TiO₂/CsPbI₂Br/spiro-OMeTAD/Au. FTO/glass substrates were successively cleaned in an ultrasonic bath of water, acetone and isopropanol alcohol for 10 min. Then the surface of substrates was treated under UVO for 15 min to make a hydrophilic surface. TiO₂ layers (40 nm) were prepared by a chemical bath deposition method as electron transport layers. CsPbI₂Br perovskite layers were prepared by spin coating the perovskite precursors (0.208 g PbI₂, 0.165 g PbBr₂, 0.234 g CsI, or 0.243 g PbI₂(DMSO), 0.200 g PbBr₂(DMSO), 0.234 g CsI) in mixed solvent of N,N-dimethylformamide (DMF) and DMSO (4:1, v/v) with a concentration of 0.9 mg/mL for 10 s and 4000 rpm for 40 s, and the chlorobenzene was coated on the film between 14 and 16 s during the second spinning step as an antisolvent. After the spin coating, the precursor films were annealed on a hotplate at 65 or 120 °C for 10 min. Then bis[trifluoromethylsulfonfyl]imidilddithium salt (Li-TFSI, Sigma Aldrich) and 4-tert-butylpyridine (TB, Sigma Aldrich) codoped 2,2′,7,7′-tetrakis(N,N-dimethoxyphenylamine)-9,9′-spirobifluorene (spiro-OMeTAD) solution in chlorobenzene (90 mg mL⁻¹) was coated on inorganic perovskite layer at 5000 rpm for 30 s to form the hole transport layer. Finally, a gold film (~80 nm) was thermally evaporated on spiro-OMeTAD by using a shadow mask to form a device active area of 9 mm² as the top electrode. The flexible inorganic PSCs were fabricated with a structure of PET/ITO/Nb₂O₅/CsPbI₂Br/spiro-OMeTAD/Au. The ITO film was deposited on the PET substrates by a magnetron sputtering method. The MgF₂ was deposited on the back of PET by electron beam evaporation as an antireflection coating. The MgF₂/PET/ITO flexible substrate has an average transmittance of ~86% in the spectrum region of 400–800 nm and a sheet resistance of ~8 Ω sq⁻¹. The flexible substrate was cleaned with deionized water and ethanol in an ultrasonic bath. The Nb₂O₅ films (60 nm) were deposited on the flexible substrates by an e-beam evaporation method as the electron transport layer. The CsPbI₂Br perovskite film, spiro-OMeTAD layer and Au electrode were prepared with the same procedure as on the rigid substrates.

**Device Characterization:** Top-view and cross sectional images of samples were analyzed by field-emission SEM (HITACHI, SU-8020). XRD spectra were obtained using a D/MAX 2400 diffractometer with Cu Kα radiation (Rigaku). The absorption spectra of DMSO adducts were collected using a Keithley 2400 series sourceMeter under the illumination of an AM 1.5G at 100 mW cm⁻² irradiance generated by a SAN-ELECTRIC XES-40S2-CE solar simulator, with the intensity calibrated by a NREL-traceable KG5 filtered silicon reference cell. Both forward and reverse scans were recorded at a scan rate of 0.03 V s⁻¹. The EQE spectra of the PSCs were recorded by a QTest Station 2000ADI system. The sheet resistance of ITO film deposited on PET was measured by an SB118 four-probe meter.

**Supporting Information**

Supporting Information is available from the Wiley Online Library or from the author.

**Acknowledgements**

H.J. and J.F. contributed equally to this work. The authors acknowledge all support from the National Key Research and Development Program of China (2016YFA0202403), the National Natural Science Foundation of China (61704101), the National Natural Science Foundation of Shaanxi Province (2017JM6020), the Fundamental Research Funds for the Central Universities (GK201702003, GK201603053), the 111 Project (B14041), the National Natural Science Foundation of Shaanxi Provincial Department of Education (2017KW-023).

**Conflict of Interest**

The authors declare no conflict of interest.

**Keywords**

CsPbI₂Br, flexible, high performance, high stability, low temperature

Received: July 15, 2018
Revised: August 4, 2018
Published online: September 15, 2018
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