A new sequential-vapour-deposition method is demonstrated for the growth of high-quality CH$_3$NH$_3$PbI$_3$ perovskite films. This has enabled the all-vapour, low-temperature fabrication of hole-conductor-free planar perovskite solar cells consisting of only a CH$_3$NH$_3$PbI$_3$/C$_{60}$ bi-layer sandwiched between two electrical contacts, with a power conversion efficiency of 5.4%.

Organometallic trihalide perovskites with the general formula (RNH$_3$)MeX$_3$ (where R is an organic group, Me is Pb or Sn, and X is a halogen I, Br, or Cl) have recently emerged as new generation light harvesting materials in excitonic solar cells. In particular, methylammonium (MA) lead triiodide (CH$_3$NH$_3$PbI$_3$ or MAPbI$_3$) has attracted great deal of attention since it was first applied as the light absorber in mesoscopic solar cells. Within a short period of time the power conversion efficiency (PCE) of MAPbI$_3$-based solar cells has shot up dramatically to 16.2%.

This rapid rise in the performance is the result of the innate light harvesting properties of MAPbI$_3$, including favourable direct band gap, large adsorption coefficient, high carrier mobilities and long carrier (balanced) diffusion lengths. With regards to the latter, Xing et al. showed that the carrier diffusion length in solution-processed MAPbI$_3$ thin films is at least 100 nm, despite the non-ideal nature of the solution-spun MAPbI$_3$ films. Higher PCEs of ~12% were obtained by Malinkiewicz et al. and Chen et al. in planar (non-mesoscopic) solar cells based on better quality MAPbI$_3$ films of ~300 nm thickness. This suggests that maximizing the quality (coverage, crystallinity, texture) of MAPbI$_3$ films can lead to carriers diffusion lengths ~300 nm, which is the key to realizing planar perovskite-based solar cells with high efficiencies.

However, reliable deposition of high-quality films of phase-pure MAPbI$_3$ perovskites with full coverage and high crystallinity still remains a challenge. One-step solution-spun MAPbI$_3$ generally results in films with pinholes due to high reaction rate between MAI and PbI$_2$. To address this issue, Burschka et al. developed a two-step method, where mesoporous TiO$_2$ is first infiltrated by solution-processed PbI$_2$, followed by dipping it in a MAI solution for the in situ formation of MAPbI$_3$. However, in the case of planar solar cells, where a mesoporous TiO$_2$ scaffold is not used, several hours are needed for the complete conversion of MAPbI$_3$, which can result in the peeling of the films. In another study involving planar solar cells, the dipping process was replaced by extended annealing of the solution-processed PbI$_2$ film in a MAI-vapour-rich N$_2$ atmosphere at 150 °C. However, this process may be not amenable to producing uniform MAPbI$_3$ films on organic substrates. Meanwhile, Liu et al. and Malinkiewicz et al. used dual-source co-evaporation deposition to prepare uniform, pinhole-free films of MAPbI$_3$, or chlorine-doped MAPbI$_3$, where the resulting planar solar cells delivered one of the highest PCEs. However, careful control of evaporation rates of the organic and the inorganic precursors is needed to achieve proper stoichiometry in the deposited films.

To that end, we demonstrate here a facile sequential-vapour-deposition (SVD) approach for the growth of high-quality MAPbI$_3$ films, which has enabled the fabrication of simple perovskite-based planar solar cells consisting of a MAPbI$_3$ perovskite/C$_{60}$ fullerene bi-layer sandwiched between two electrical contacts (indium tin oxide (ITO) coated glass and thermally-evaporated Ag). A maximum PCE of 5.4% is achieved in these solar cells. To our knowledge, this type of bi-layer architecture, which is devoid of any additional blocking layer, any mesoporous scaffold (e.g. TiO$_2$, ZnO, or Al$_2$O$_3$), and any additional conducting organic layers, constitutes the simplest perovskite-based working solar cell reported thus far. Especially, while several groups have hole-conductor-free
mesoscopic perovskite solar cells, this is the first report of planar perovskite solar cells without use of hole conductors.

Fig. 1 is a schematic diagram of the SVD method for the growth of MAPbI₃ films. A nanostructured porous PbI₂ film is first vapour-deposited (Fig. 1A), followed by the vapour-deposition of MAI (Fig. 1B), which reacts \textit{in situ} with the PbI₂ film (Fig. 1C). The freshly prepared MAPbI₃ film is further annealed at 100 °C for 30 min to produce a textured film (Fig. 1D). Note that strong texture in perovskite films have been suggested to be beneficial, most likely due to their improved carriers-transport properties.12,13

Detailed experimental procedures, including SVD growth of the films and solar cells fabrication, are presented in the accompanying (ESI†). Also presented in ESI are characterization procedures, including X-ray diffractometry (XRD), scanning electron microscopy (SEM), optical microscopy and ultraviolet-visible (UV-vis) optical spectroscopy, and procedures for solar cells testing.

Fig. 2 shows XRD patterns from the films at different stages of the SVD growth, and the evolution of the surface morphology of the thin films. The XRD pattern in Fig. 2A confirms the presence of layered PbI₂ (space group $P3m1; a = 4.600(2)$ Å, $b = 4.600(2)$ Å, $c = 6.9926(9)$ Å) in the film after the first step, and shows a strong 001 texture. The corresponding SEM image in Fig. 2B shows full-coverage, smooth film consisting of randomly-oriented packing of plate-like PbI₂. There is some amount of porosity between the adjacent PbI₂ plates in the film. The thickness of the PbI₂ plate-like structures is estimated at ~20–30 nm (see Fig. S1 in ESI†), which is responsible for the broadening of the XRD peaks in Fig. 2A. In contrast, solution-processed PbI₂ films prepared by spin-coating are relatively rough, with equiaxed grains of PbI₂ of few hundred nanometers size.4 Fig. 2C is XRD pattern of PbI₂ film exposed to MAI vapour for 5 min, showing the presence of both PbI₂ and MAPbI₃. The corresponding SEM image in Fig. 2D shows features such as unreacted PbI₂ and pinholes. Visually, the side exposed to MAI vapour appears black (MAPbI₃), while the back side appears yellow (PbI₂) through the glass. This indicates that the PbI₂ + MAI $\rightarrow$ MAPbI₃ reaction is diffusion limited. After additional 10 min of MAI vapour exposure the reaction is complete, as confirmed by XRD (Fig. 2E); the XRD pattern shows phase-pure tetragonal MAPbI₃ (space group $I4/mcm; a = b = 8.8745(7)$ Å, $c = 12.665(2)$ Å) and the absence of PbI₂. The corresponding SEM image (Fig. 2F) shows a uniform, smooth film of polycrystalline MAPbI₃ with a grain size of ~500 nm. The entire thickness (~350 nm) of the MAPbI₃ film appears dark visually. Heat-treatment (100 °C, 30 min.) of the MAPbI₃ perovskite film results in the development of strong 110 texture (Fig. 2G), and a slightly distorted structure ($a = 8.876(5)$, $b = 8356(2)$ Å, $c = 12.530(6)$ Å). SEM image in Fig. 2H shows no grain coarsening as a result of the heat-treatment, but shows faceting of the individual grains. How this texture develops during this modest heat-treatment is not known at this time.

It appears that the nanoporous nature of the vapour-deposited PbI₂ film (Fig. 2B), with its large specific surface area, allows easy ingress and contact with MAI vapour, promoting rapid and more uniform reaction between PbI₂ and MAI. This results in phase-pure MAPbI₃ films that are pinhole-free, uniform, and smooth (Fig. 2F). Since the film thickness is ~350 nm, and the size of the MAPbI₃ grains is ~500 nm, most of the MAPbI₃ grains span the entire thickness of the film. In other words, majority of the grain boundaries in the SVD-processed MAPbI₃ films are expected to run vertically between the substrate and the film surface, and that the horizontal grain boundaries across the path of carriers transport are likely to be in the minority.

Fig. 3A shows the UV-vis absorbance spectrum of the MAPbI₃ perovskite film (on ITO) prepared by the SVD method and the corresponding differential transmission ($\Delta T/T$) spectrum (inset is an optical photograph showing dark-colored film). The CH₃NH₃PbI₃ perovskite film exhibits strong adsorption of UV-vis light up to ~790 nm wavelength, which is consistent with what is reported in the literature.8,14,15 However, from the
differential transmission spectrum, the SVD-processed CH$_3$NH$_3$PbI$_3$ perovskite film shows only one intense photo-bleaching peak at $\sim$760 nm which is assigned to the direct band gap transition. The broad photobleaching peak at $\sim$480 nm, which is typically observed in MAPbI$_3$ perovskite films, is virtually absent in the $\Delta T/T$ spectrum in Fig. 3A. This is probably related to unique band structure in the SVD-processed MAPbI$_3$ perovskite films that exhibits unique crystal morphology. These distinct UV-vis absorption characteristics of the SVD-processed MAPbI$_3$ perovskite films also indicate the likelihood of an efficient photo-induced charge transfer during the solar cell operation.\(^6\)

Fig. 3B is a color-enhanced cross-sectional SEM image of a typical MAPbI$_3$/C$_60$ bilayer solar cell fabricated in this study, illustrating the simple cell architecture. All three layers—MAPbI$_3$, C$_60$, Ag—are vapour deposited (see ESI†). The energy-levels diagram of this simple cell architecture is shown in the Fig. 3C inset. Here the MAPbI$_3$ film serves as absorber, electron-donor, hole-conductor, and electron-blocking layer. Whereas the C$_60$ layer serves as electron-acceptor, electron-conductor, and hole-blocking layer. Since MAPbI$_3$ is a good hole-conductor, additional hole-conducting layers typically used in perovskite-based solar cells can be eliminated while retaining high PCEs.\(^7,19\) Furthermore, the widely used mesoporous TiO$_2$ electron-acceptor/conductor scaffold and/or dense TiO$_2$ hole-blocking layer, which require high-temperature processing, have been eliminated in these solar cells.\(^7,19\) Efficient electron-hole dissociation occurs at the MAPbI$_3$/C$_60$ interface, making C$_60$ a promising candidate as a non-oxide electron-acceptor/conductor and hole-blocking layer in perovskite-based solar cells.\(^14,15\)

Fig. 3C shows a typical current density ($J$) – voltage ($V$) response of the MAPbI$_3$/C$_60$ bilayer solar cell under AM1.5G simulated one sun illumination, and the solar-cell performance parameters are reported in the inset. Ten solar cells were tested, and their performance data are summarized in Table S1 (see ESI†), with the PCE ranging from 4.1% to 5.4%. Considering the simplicity of these solar cells, a maximum PCE of 5.4%, an open-circuit voltage ($V_{OC}$) of 0.8 V, and a short circuit current density ($J_{SC}$) of 13.6 mA cm$^{-2}$, are promising, and they can be attributed to the high quality of the SVD-processed MAPbI$_3$ films. The estimate of the maximum $V_{OC}$ is given by:\(^14\)

$$V_{OC} = \left( E_{HOMO} - E_{LUMO} \right) / e \quad (1)$$

Substituting the values from the energy-levels diagram in Fig. 3C (inset) in eqn (1), the maximum $V_{OC}$ is estimated at 1.0 V for the MAPbI$_3$/C$_60$ heterojunction, representing a 20% loss in the measured $V_{OC}$ (0.8 V) in the MAPbI$_3$/C$_60$ bilayer solar cell (Fig. 3C).

Jeng et al.\(^14\) and Chiang et al.\(^20\) report PCEs of 1.6% and 3.62%, respectively, for solution-processed MAPbI$_3$/C$_60$ solar cells, but their solar cells also contain additional layers of poly[3,4-ethylenedioxythiophene] poly(styrene-sulfonated) (PEDOT:PSS) and bathocuproine (BCP). The PEDOT:PSS layer is the hole transporter and it appears necessary for one-step solution processing of MAPbI$_3$,\(^18\) and the C$_60$ layer is used as a hole-blocker. The voltage loss in MAPbI$_3$/C$_60$ solar cells by Jeng et al.\(^17\) is 45%, whereas cells by Chiang et al.\(^19\) show a lower loss of 16%. The use of a layer of a C$_60$ derivate—(6,6)-phenyl-C$_{61}$-butyric acid methyl ester (PC$_{61}$BM)—instead of the C$_60$ layer, in solution-processed MAPbI$_3$/PC$_{61}$BM solar cells results in higher PCE (7.4%),\(^18\) however, those cells also use the additional layer of PEDOT:PSS. The maximum estimated $V_{OC}$ for these MAPbI$_3$/PC$_{61}$BM is 1.23 V, and the measured $V_{OC}$ in those cells is 0.91 V (ref. 18) or a 26% loss. Thus, the voltage loss in the simple MAPbI$_3$/C$_60$ bi-layer solar reported here is one of the lowest for solar cells based on MAPbI$_3$/fullerene heterojunctions, which is attributed to the improved coverage of perovskite film by SVD method.

With regard to $J_{SC}$, the measured value of 13.6 mA cm$^{-2}$ reported here is the highest among all the MAPbI$_3$/fullerene heterojunction solar cells reported so far.\(^14,15,20\) This is attributed to the relatively thicker and denser SVD-processed MAPbI$_3$ films used here that are able to absorb light more efficiently. The fill factor (FF) of 50% is relatively low in these MAPbI$_3$/C$_{60}$ solar cells, which could be due to various factors, including non-
ideal electrical contacts. Thus, there is plenty of room for improvement in this regard through further optimization of the ITO surface and the C₆₀/Ag interface.

Conclusions

An SVD method is demonstrated for the growth of high-quality MAPbI₃ films, and the possible growth mechanisms are elucidated. This constitutes a new contribution to the menu of processing methods available for the growth of MAPbI₃ perovskite films. The resulting MAPbI₃ films are pinhole-free, uniform and smooth, and most of the textured MAPbI₃ grains within the films span the entire thickness of the film. The high quality of the MAPbI₃ films allowed us to fabricate hole-conductor-free planar MAPbI₃ perovskite solar cells at low temperature (100 °C maximum) that deliver a promising PCE of 5.4% with Vₜₚ of 0.8 V. While the simple bi-layer cell architecture is used here to demonstrate the efficacy of the SVD process, high-quality MAPbI₃ films grown by the SVD process can be used in more complex solar cell architectures for much higher performance, and also in other future optoelectronic devices.

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Notes and references