Preparation of SnO_2 asElectronTransportlayerfor Organic and Inorganic Perovskite Solar Cells: A Review.

ABSTRACT

The fascinating behavior of electron transport in halide perovskite solar cells has piqued the interest of designers of semiconductor SnO_2 nanoparticles (PSC). The goal of this research is to look at several techniques for manufacturing semiconductor SnO_2 films for use as electron transport layers in PSC. To comprehend the link between the quality of nanostructured SnO_2 films and the performance of solar cells, special attention is devoted to the production and properties of the SnO_2 particles/films. The spin-coating deposition of SnO_2 nano fluids generated by surface modification of SnO_2 nano-colloids has been one of the key techniques for obtaining SnO_2 layers. It has also been reported that preparing SnO_2 nanoparticles using Tin (IV) salts results in a smooth SnO_2 film. A light-to-electricity conversion efficiency of about 20% has been claimed in many PSC papers. One benefit of adopting SnO_2 materials is that they have substantially greater conductivity than TiO_2. This work also discusses the production of SnO_2 nanoparticles, a different method of generating SnO_2 electron transport materials that may be accomplished by the freeze-drying of Tin (IV) precursors. SnO_2 crystal formation may be regulated at temperatures as low as 60^0C.

Keywords: [TiO_2,SnO_2 Nanoparticles, ElectronTransport, PerovskiteSolar Cells *} (Arial,inclined, 10 font, justified)*

1. INTRODUCTION

Over the last several decades, there has been a decrease in the supply of fossil fuels and an increase in global energy demand, resulting in increased environmental damage. This has accelerated the development of renewable energy sources, with solar power being one of the leading possibilities owing to the sun's ability to give the ultimate answer to the dilemma of sustainable energy supply. Solar cells and passive/active solar thermal systems are the two most common ways to create solar electricity. When it comes to solar cells for electric power production, there are many methods for harvesting solar energy, the most popular of which are traditional solid-state solar panels. The disadvantages of these silicon-based solar panels include their high manufacturing costs and bad environmental effects. Different types of solar cells have appeared in recent years, each promising cheap manufacturing costs, minimal environmental impact, and great efficiency, such as perovskite solar cells (PSC) [1] and dye-sensitized solar cells (DSSC) [2]. One of the electrodes in these solar cells is made of nano-crystalline material such as TiO_2 and/or SnO_2, creating the semiconductor layer for the photon-electron transfer process. The nano-crystalline substance is often used. To put over a clear conducting glass to create a high surface coverage of light-absorbing materials, which is required for high-performance devices.

Tin (IV) oxide (SnO_2) has recently been investigated as a possible electron transport material as an alternative to TiO_2. SnO_2 has been extensively explored, for example, concerning perovskite solar cells (PSCs), owing to their advantageous properties such as high electron mobility (100-200 cm^2 V^{-1} s^{-1}) and a broad bandgap of 3.6 eV compared to

3.2 eV for TiO_2[3]. The high mobility may facilitate quicker electron transit, lowering the likelihood of photoinduced electron recombination. Furthermore, SnO_2 creates a homo-junction with the FTO substrate, which eliminates the high contact resistance reported in hetero-junctions created with other oxides such as TiO_2. Despite the obvious benefits over TiO_2, there are several problems about utilizing SnO_2 as an electron transport layer, the primary one being that it degrades at higher temperatures. Much research has been conducted to demonstrate that the efficiency of solar cells may be boosted even further by employing SnO_2 instead of TiO_2. This study describes important breakthroughs in the fabrication of SnO_2 thin films, as well as the unique properties of SnO_2 as electron transport layers in PSCs (Tables 1 and 2).

2. MATERIAL AND METHODS

2.1Synthesis of Tin oxide layer and perovskite solar cells applications

Table1. Overview of the usual SnO_2 film deposition process and PSC performance. MA and FA are abbreviations for Methylammonium and Formamidinium ions, respectively.

Deposition technique of SnO_2	Perovskite	Jsc(mA/cm^2)	Voc(V)	FF	η (%)	Ref.
Sol-gel process (Spin-coating of Tin salt, Annealing)	$CH_3NH_3PbI_3$	22.83	1.11	0.64	16.02	[4]
Deposition of SnO_2colloidal solution (Spin-coating)+Annealing	$(FAPbI_3)_{0.97}(MAPbBr_3)_{0.03}$	24.87	1.09	0.74	20.27	[5]
Deposition of SnO_2colloidal solution (Spin-coating)+Annealing	$FA_{0.95}Cs_{0.05}PbI_3$	24.57	1.11	0.79	21.60	[6]
Deposition of SnO_2colloidal solution (Spin-coating)+Annealing	$(FAPbI_3)x(MAPbBr_3)_{1.x}$	24.1	1.1	0.78	21.30	[7]
Sol-gel process (Spin-coating of Tin salt, Annealing)	$MAPbI_3$	22.66	1.07	0.72	17.61	[8]
Deposition of SnO_2 colloidal solution (Spin-coating)+ Annealing	$MAPbI_3$	24.28	1.15	0.76	21.38	[9]
Electrodeposition (Tin sailts)+Annealing	$MAPbI_3$-xClx	18.65	1.02	0.79	14.97	[10]

Deposition of SnO_2 colloidal solution (Spin-coating)+ Annealing	$CH_3NH_3PbI_3$	20.11	1.11	0.64	14.36	[11]
Magnetron sputtering	$CH_3NH_3PbI_3$	21.94	0.99	0.67	14.63	[12]
Atomic layer deposition	$Cs_{0.05}(MA_{0.17}FA_{0.83})_{0.95}Pb(I_{2.7}Br_{0.3})$	22.1	1.07	0.75	17.80	[13]

High-temperature processed TiO_2 was commonly employed as the electron transport layers in high-performance lead halide perovskite solar cells. Ke et al. [14] published one of the first investigations on SnO_2-based perovskite solar cells, suggesting that low-temperature solution-processed nanocrystalline SnO_2 might be an effective alternative to TiO_2. SnO_2 was synthesized in this work using a solution technique, i.e. spin-coating of $SnCl_2$ precursor, which may be manufactured at room temperature. This was followed by 1 hour of thermal annealing in air at 180 °C. Before Perovskite deposition, the thin films were exposed to UV-ozone for 15 minutes. The film was composed of nanoscale grains, according to SEM and TEM examination, and the SnO_2 was crystallized. When the FTO substrate was coated with the SnO_2 nanocrystalline film, atomic force microscopy pictures revealed that the surface grew smoother. When tested using a reverse voltage scan, the top performing perovskite cell with a 60 nm-thick SnO_2, $CH_3NH_3PbI_3$ (600 nm), and Spiro-OMeTAD attained a PCE of 17.21 % (Voc: 1.11 V, Jsc: 23.27 mA cm^{-2}, and FF: 0.67). The PCE for a forward voltage scan of the same cell was 14.82 %, Voc was 1.11 V, Jsc was 22.39 mA cm^{-2}, and FF was 0.60. The hysteresis of the perovskite solar cells with the SnO_2 layer was minimal. They concluded that the improved charge transfer (a faster electron injection process) at the SnO_2/perovskite interface might account for some of the reduced hysteresis found in the PSC. This work opened the door for improved performance of lead halide perovskite solar cells.

Jiang et al. [5] exhibited improved electron extraction of SnO_2 for high-efficiency planar-structure $HC(NH_2)_2PbI_3$-based PSC. Commercial SnO_2 colloid precursor (tin (IV) oxide, 15% in H_2O colloidal dispersion) was spin-coated onto ITO substrates and baked for 30 minutes on a hot plate in ambient air at 150°C. The SnO_2 film's mobility was predicted to be 1.9 x 10^{-3} $cm^2V^{-1}s^{-1}$. The perovskite layer was synthesized using a two-step spin coating process after the SnO_2 electron transport layer was deposited. PbI_2 in dimethylformamide (DMF) was spin-coated before being annealed at 70°C for 30 minutes. Second, an FAI:MABr:MACl solution in isopropanol was spin-coated onto the PbI_2. Under reverse scan, the top performing device utilizing SnO_2 nanoparticles generated a V_{OC} of 1.09V, Jsc of 24.87mAcm^{-2}, FF of 74.77 %, and PCE of 20.27 % (Spiro-OMeTAD was used as a hole-conductor.). The identical device had a V_{OC} of 1.09V, a J_{SC} of 24.88 mAcm^{-2}, an FF of 75.73 %, and a PCE of 20.54 % during forward's scan. When compared to $CH_3NH_3PbI_3$, the optical response edge has been extended to 820 nm. The scientists also showed that SnO_2-based devices outperformed TiO_2-based devices in terms of photostability, however the mechanism remained unclear.

The use of surface modified tin oxide (SnO_2) has also been shown to be an efficient method for high-efficiency PSC. Yang et al. recently described a planar-type perovskite solar cell (PSC) with SnO_2 modification utilizing a chelating chemical, EDTA [15]. In deionized water, EDTA was dissolved.

Separately, the SnO_2 aqueous colloidal dispersion was made to eliminate leftover solvent. The EDTA and

SnO_2 solutions were combined in a volume ratio of 1:1, and the milky-white 'E-SnO_2' colloidal solution, i.e. SnO_2 nanofluid, was created using a hot plate at 80 °C. Finally, the E-SnO_2 films were produced by spin-coating followed by 30 minutes of drying in a vacuum oven at 60 °C. AFM scans of the SnO_2-coated ITO substrates indicated that the E-SnO_2 film had the least roughness of 2.88 nm. The alignment of energy bands in perovskites and SnO_2 was also established. The Fermi level of E-SnO_2 was discovered to be quite near to the conduction band of perovskite. The authors demonstrated that SnO_2 films have a high average transmittance in the visible range. Furthermore, the electron mobility of E-SnO_2 was 2.27103 $cm^2V^{-1}s^{-1}$, much greater than that of unmodified SnO_2 (9.92104 $cm^2V^{-1}s^{-1}$). $FAPbI_3$ was employed as an active light absorber because of its suitable band gap, with a little quantity of Cs added to increase phase stability. It was discovered that continuous pinhole-free films were formed when perovskite films were deposited on SnO_2 substrates. Notably, with the E-SnO_2 substrates, the average perovskite grain size increased to about 828 nm. The EDTA-based device had a PCE of 16.42 %, Jsc =22.10 $mAcm^2$, Voc =1.08 V, and FF =0.687. The device with an unchanged SnO_2 substrate has a PCE of 18.93%, Jsc=22.79 $mAcm^2$, Voc=1.10V, and FF=0.755. When E-SnO_2 was used as the ETL, the PCE rose to up to 21.60 % (the Jsc, FF, and Voc were increased to 24.55 mA cm^2, 0.792, and 1.11V, respectively). The greater Jsc and FF were attributed to SnO_2-enhanced electron mobility, which may efficiently extract electrons. The higher Voc might be explained by the lower energy level of E-SnO_2 and perovskite.

The passivation impact of a fullerene derivative with 2-hydroxyl anchoring groups on the performance of the SnO_2 electron transport layer in PSC has been reported by Liu et al. . Through coordination to Sn, the hydroxyl groups at the end of the long alkyl chain in C9 were introduced to passivate the oxygen vacancies on the surface of SnO_2. In other words, the fullerene-modifying layer might effectively passivate the SnO_2 layer surface flaws. Using a water-based SnO_2 colloidal solution, a thin coating of SnO_2 nanoparticles was spin-coated on the ITO substrate and annealed at 150 °C for 30 minutes. The C9- fullerene derivative was soaked in chloroform and spin-coated onto the SnO_2. In a N_2 environment, the Perovskite film was further spin-coated. The perovskite precursor solution was placed over SnO_2, spin-coated, then annealed for 10 minutes at 150 °C. A configuration of ITO/SnO_2/C9- fullerene /($FAPbI_3$)x($MAPbBr_3$)1-x/spiro-OMeTAD/Au was studied using Spiro-OMeTAD as a hole-transport layer. The highest PCE of the C9-fullerene modified devices was 21.3 % with low hysteresis, which was greater than the control devices of bare SnO_2 (PCE: 20.0%). Fullerene derivatives with anchoring hydroxyl groups were shown to be useful in the materials interface engineering of SnO_2-based PSCs in this study.

Bilayer SnO_2 has also been shown to be an efficient electron transport layer for PSC [8]. Yi et al. formed a bilayer structure by filling the pinholes in the sol-gel SnO_2 layer with SnO_2 nanoparticles. For ETL, a sol-gel SnO_2 precursor solution containing Tin (IV) chloride pentahydrate was spin-coated on ITO within an N_2 filled glovebox and annealed at 200 °C for 60 minutes at ambient temperature. SnO_2 colloid dispersion was spin-coated on a UVO-treated substrate and annealed for 30 minutes at 150 °C. The methylammonium lead iodide perovskite films ($CH_3NH_3PbI_3$) were made in a single process. The surface of the SnO_2 top layer (bilayer structure) had an amorphous-like shape and no pinholes were seen, while only sol-gel SnO_2 had visible pinholes in the film. The rough surface of double layered SnO_2 ETL was 1.69 nm as measured by AFM. The average PCE of the Bilayer SnO_2-based PSC has been enhanced from 12.97 % to 16.84 % with thin-layer SnO_2 nanoparticles. The biggest cause was the 23.7 % increase in FF. The disclosed bilayer SnO_2 ETL is likely to offer new avenues for the development of highly efficient PSC.

The approach of Liu et al. [9] was used to reduce the hysteresis of I-V curves for SnO2-based PSC. By stirring at room temperature, the aqueous SnO_2 colloidal dispersion was combined with NH_4Cl to generate the NH_4Cl-SnO_2 precursor. The NH_4Cl-SnO_2 layers were created by spin-coating them onto clean ITO substrates and then annealing them to remove the solvent. On top of SnO_2 was placed the $MAPbI_3$ perovskite coating.ITO/SnO_2/perovskite/Spiro-OMeTAD/Ag was used in the devices. The perovskite solar cells containing NH_4Cl-induced coagulated SnO_2 colloids generated a PCE of 21.38 % with minor hysteresis, while the reference solar cell produced a PCE of 18.71 % with hysteresis. They also said that the device's stability may be greatly enhanced.

Ko et al. demonstrated that SnO_2 electrodeposition on FTO may be employed in planar heterojunction perovskite solar cells [10]. Using a three-electrode system (working electrode: FTO, counter electrode: platinum plate, reference electrode: Ag/AgCl electrode) and a water-based solution of $SnCl_2H_2O$ and nitric acid, a chrono-voltammetry approach was designed for the electrodeposition of Sn nanospheres on FTO substrate. The nanospheres were heated in air for 30 minutes at 400 °C to convert to SnO_2. $TiCl_4$ treatment was also used, using a $TiCl_4$ solution at 70 °C for 30 minutes and the substrates drying in air at 150 °C. In a glove box, a combination of PbI_2 and $PbCl_2$ diluted in N, N-dimethylformamide was spin-coated on the SnO_2-coated FTO and dried at 70 °C to form the perovskite layer. A methylammonium iodide solution was spin-coated and then annealed in the ambient atmosphere for 75 minutes at 105 °C. The HTM was a poly[bis(4-phenyl)(2,4,6-trimethylphenyl)amine solution. After 150 seconds (about 2 and a half minutes) of deposition, the device's PCE was 9.11 %, with short-circuit current density, open-circuit voltage, and fill factor of 17.84 mA/cm2, 1.03V, and 0.496, respectively. Despite increasing the deposition time to 180 s, the better Jsc resulted in a higher PCE of 10.0 %. The adoption of a 210-second deposition period reduces the PCE (8.22 %).

Aside from the previously reported solution-processed SnO_2 film deposition, Li et al. demonstrated the impact of UV treatment of low-temperature processed SnO_2 on the performance of PSC [11]. They created a dense layer by spin-coating a water-based SnO_2 precursor and then treating it with UV ozone. The SnO_2 thin films were made by spin-coating the SnO_2 precursor solution (concentrations of 10, 15, 20, and 30%) on ITO substrates and drying them at 50 °C. The substrates were then cleaned using an ultraviolet ozone cleaner for

60 minutes at 60 ^{0}C. Each layer of solar cells was manufactured at temperatures below 90 °C. The device architectures were ITO/SnO_2/$MAPbI_3$/Spiro-OMeTAD/Au planar hetero-junction PSC. The performance was optimum when the concentration of SnO_2 was 20%, with Jsc of 20.11 mA/cm^2, Voc of 1.11 V, FF of 0.643, and PCE of 14.36 %.

Sun et al. [12] also reported a vacuum produced SnO_2 film. They produced the film satisfactorily using radio frequency reactive magnetron sputtering at room temperature. The resulting SnO2 thin films had reduced surface roughness than the FTO substrate, which improved the interface morphology with the perovskite layers. The roughness of the FTO glass without sputtering was 31.8 nm, whereas the roughness of the sputtering sample was 30.2 nm. The sputtering method smoothed and uniformed the perovskite coating, minimizing flaws in interfacial contact. Due to weak Jsc and FF, planar perovskite cells based on bare FTO exhibited a PCE of just 5.08 %. PCE of the device was 12.02 % when reactive sputtering was used to deposit an electron transport layer (Jsc: 20.20 mA/cm^{-2}, Voc: 0.95, and FF: 0.62).

Kuang et al. reported on plasma-assisted atomic-layer SnO_2 deposition for PSC [13]. At 200 °C, tetrakis (dimethylamino)tin (TDMASn) was used as a

precursor to form a SnO_2 film with a low electrical resistivity of 1.8 1013 cm, a carrier density of 9.6 1019 cm3, and a high mobility of 36.0 cm^2 /V s. As substrates, ITO layers were employed, and SnO_2 layers with a thickness of 15 nm were deposited at temperatures ranging from 50 to 200 °C. Prior to perovskite deposition, the SnO_2 layers were pretreated with O_2 plasma at ambient temperature. Planar PSCs of $Cs_{0.05}(MA_{0.17}FA_{0.83})_{0.95}Pb(I_{2.7}Br_{0.3})$ were created. The top performing devices utilizing 50 and 200 °C-processed SnO_2 attained PCEs of 17.5 and 17.8 %, respectively.

Scientists recently shown for the first time that crystalline SnO_2 nanoparticles may be created using a low-temperature approach utilizing a dry-freezing technique. At less than 30^0 C, $SnCl_2$ was adopted for dry freezing as a starting material to generate the precursor solution of water and methanol combination. This approach efficiently dehydrated the amorphous Sn (II)-containing precursor, resulting in crystalline SnO_2 nanoparticles [16]. On the Transmission Electron Microscope, nanoparticles as small as 5 nm were visible. The XRD pattern revealed that SnO_2 nanocrystals were produced during the dry freezing procedure. Device applications using SnO_2 as an electron transport layer in PSC are currently being developed.

3. RESULTS AND DISCUSSION

3.1 Perovskite solar cells with tin oxide/titanium oxide hybrid layers

Table2. Examples of SnO_2/TiO_2 film deposition techniques and PSC performance.

Depositiontechnique of SnO_2/TiO_2	Perovskite	Jsc(mA/cm^2)	Voc(V)	FF	η (%)	Ref.
TiO_2nanoparticles coated by an amorphous SnO_2 (Spin-coating)	$CsI + (FAPbI_3)_{0.87}(MAPbBr_3)_{0.13}$	22.51	1.168	0.776	20.40	[17]
Three-stepchemical bath	$(FAPbI_3)_{0.3}(MAPbI_3)_{0.7}$	23.38	1.122	0.778	20.40	[18]
Magnetronsputtering (TiO_2)/Deposition of SnO_2colloidal solution (Spin- coating)+ Annealing (SnO_2)	$Cs_{0.05}(MA_{0.17}FA_{0.83})_{0.95}Pb(I_{0.83}Br_{0.17})_3$	23.28	0.980	0.670	15.39	[7]

Tavakoli et al. [17] described a mesoscopic oxide double layer (SnO_2/TiO_2) used as an electron selective contact for PSC. This electron selective layer was made up of TiO_2 nanoparticles that were covered with amorphous SnO_2. SnO_2 precursor solution was used to modify the surface of mesoporous-TiO_2 ($SnCl_2$ dissolved in ethanol). This solution was spin-coated on top of mesoporous-TiO_2, then the films were annealed at 180 °C. SEM tests revealed that the grain size of perovskite film generated on amorphous SnO_2 was somewhat greater than that of perovskite film formed on top of the bare mesoporous-TiO_2 layer. This meant that the number of nucleation sites for amorphous SnO_2 was decreased, resulting in greater perovskite grain size. The XRD measurements revealed that the spin-coated SnO_2 film was amorphous at 180 °C and was transformed to crystalline SnO_2 after annealing at 450 °C. FTO glass covered with a compact TiO_2 layer, a 150 nm-thick mesoporous-TiO_2, a thin layer of SnO_2, a 300 nm-thick perovskite film, a 150 nm-thick spiro-OMeTAD, and gold contact comprised the device. Hysteresis in device I-V curves was reduced, and carrier recombination was also slowed. Consequently, the PCE of mesoporous-TiO_2/amorphous SnO_2 was 20.4 % (Jsc: 22.51mA/cm^2, Voc: 1.168 V, and FF: 77.6 %). The PCE of the reference cell, which used bare mesoporous-TiO_2, was 19.14 % (Jsc: 22.21 mA/cm^2, Voc: 1.098 V, FF: 78.5 %). They

Ding et al. [18] observed that irradiation of UV light SnO_2 nanoparticle modified TiO_2 as the ETL in PSC prevented UV degradation of the PSC, keeping 97 % of the original PCE after 60 hours. The $SnO_2@TiO_2$ layer was created using the chemical bath described below. First, a $SnCl_2$ ethanol solution was produced and kept in the freezer at 5 °C. The aqueous $TiCl_4$ solution was made by combining $TiCl_4$ with water at 0 °C and then freezing it at 5 °C. The FTO substrate was immersed in a 2M aqueous $TiCl_4$ solution. At 70 °C, the glass container was dry. The FTO substrate was washed with ethanol and water before drying at 120 degrees Celsius. After that, the substrate was treated at 70 °C with a solution made of 2M aqueous $TiCl_4$ solution and water (the molar ratio was 1:100). The FTO substrate was soaked in the solution made by combining 2M $SnCl_2$ ethanol with water after it had been chemically coated with TiO_2 nanoparticles (the molar ratio was 1:50). The glass was cured at 70 ^oC. Finally, the substrate was annealed at 140 ^oC. Perovskite solar cells performed well, with average PCEs of 21.27 %, 19.79 %, 17.21 %, and 16.31 % for active surfaces of 0.10 cm^2, 1.13 cm^2, 5.25 cm^2, and 10.56 cm^2, respectively. Their findings showed that the $SnO_2@TiO_2$ ETL may considerably improve electron extraction and reduce trap states. They also said that their low-temperature processability and lack of a spin-coating process would pave the way for PSC commercialization.

Liu et al. developed a TiO_2/SnO_2 bilayer as an electron transport layer for a carbon counter electrode-based planar-heterojunction PSC. Radio frequency magnetron sputtering was used to create a TiO_2 layer. Sputtering might completely cover the FTO substrate's surface, passivating the FTO surface flaws and decreasing recombination. The

SnO_2 layer was formed by spin-coating a $SnCl_2$ ethanol solution and then heating it at 195°C. The TiO_2/SnO_2 bilayer had the lowest RMS roughness of 9.3 nm, which was advantageous for the deposition of high-quality perovskite films. As a hole transport layer, they employed a Cs/MA/FA perovskite film coupled with Cu- Phthalocyanine (CuPc) [19]. The device achieved a PCE of 15.39 % and maintained good stability over 1200 hours.

4. CONCLUSION

Fundamental research of SnO_2 nanoparticles has advanced towards the development of renewable energy technologies, particularly as the main material in PSC. Recent improvements in the manufacture and properties of SnO_2 particles/films were reported in this work to explore the link between the quality of nanostructured SnO_2 films and the performance of PSC. Spin-coating deposition of SnO_2 nanofluids generated by surface modification of SnO_2 nano-colloid precursors has been one of the keyways in producing SnO_2 layers. Several studies have shown that PSC has a light-to-electricity conversion efficiency of about 20%. The greater conductivity of SnO_2, which is substantially higher than TiO_2, is a benefit for achieving high efficiency. Furthermore, quick electron injection at the perovskite/SnO_2 interface may minimize hysteresis. Compared to those of TiO_2 nano-crystalline systems for PSC, the design methods of SnO_2 nanoparticles comprising the chemical synthesis and thin-film generation have not been fully established so far. For future development, one study avenue would be a clearer knowledge of the link between microstructures of SnO_2 nanoparticles and device performance. As a fresh strategy towards the synthesis of semiconductor nanoparticles, our dry-freezing process may generate diverse metal oxides at low temperatures. In addition to the improvement of SnO_2 nanoparticle manufacturing, it is also necessary to optimize materials interfaces of SnO_2 layers in the PSC. Controlling SnO_2 crystal formation will explore options in the low-cost manufacture of high-efficiency perovskite solar cell modules.

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