Bilayer broadband antireflective coating to achieve planar heterojunction perovskite solar cells with 23.9% efficiency

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ABSTRACT Although perovskite solar cells (PSCs) have achieved encouraging efficiency, the photon loss at the substrate due to light reflection has not been well addressed. Light management is promising to reduce reflection loss and realize higher power conversion efficiency (PCE) of PSCs. Here, a bilayer antireflective coating (ARC) has been designed and coated onto the backside of the glass substrate of (FAPbI₃)_x-(MAPbBr₃)_{1-x} PSCs to enhance photon harvesting and consequently the device efficiency. The bottom layer of the bilayer ARC is made from a silica polymer and the top layer is made from the mixture of hexamethyldisiloxane-modified mesoporous silica nanoparticles and a fluorinated silica polymer. By adjusting the refractive index and the film thickness of each layer according to a two-layer model, enhanced glass transmittance in a broadband wavelength range can be reached, with the maximum transmittance increasing from ca. 90% to over 95%. With the bilayer ARC, the maximum short-circuit current density and PCE of (FAPbI₃)_x-(MAPbBr₃)_{1-x} PSCs can be increased from 25.5 mA cm⁻² and 22.7% to 26.5 mA cm⁻² and 23.9% with negligible changes in fill factor and open-circuit voltage. This work presents a simple yet effective strategy to enhance the efficiency of solar cells employing bilayer antireflective coatings, which can be applied to other types of solar cells.

Keywords: mesoporous silica nanoparticles, antireflective coating, perovskite solar cells, efficiency

INTRODUCTION

Organic-inorganic halide perovskite materials have strong light absorption, long carrier diffusion length and high carrier mobility, which are characteristics to realize high-performance photovoltaic devices [1,2]. The record

efficiency of perovskite solar cells (PSCs) now is 25.2% after only ten years development and is comparable to the efficiency of commercial silicon solar cells [3].

Many strategies, including energy level alignment [4–6], additive engineering [7–9] and defect passivation [10–12], have been explored to further enhance the efficiency of PSCs. For example, Wang *et al.* [4] added an In₂O₃ layer on top of the SnO₂ electron transport layer to tune the energy level alignment of the perovskite layer. The In₂O₃ layer not only promotes the electron transport at the interface, but also increases the open-circuit voltage (V_{OC}), so the power conversion efficiency (PCE) of the resultant PSC can reach 23.24%. Kim *et al.* [13] added methylammonium chloride additive into the perovskite layer, and reported a PCE of 23.48%. Jiang *et al.* [14] found that a phenethylammonium iodide layer, formed on the surface of the perovskite layer, could result in a PCE of 23.32% by reducing defects and suppressing non-radiative recombination. As encouraging results have been reported, the light reflection loss on the light incidence surface of PSCs has not been solved with satisfaction, which is a significant obstacle for further enhancement of the PCE. Luo *et al.* [15] recently proposed a creative antireflective method using SnO₂/TiO₂-Cl bilayer as the antireflective, cascaded electron transport layer (ETL) to reduce light loss and enhance device efficiency. However, the materials here should be deliberately designed to match the energy levels at the interface with perovskite, and a precise control of film thickness is also essential to enable antireflection effect, which means that this method may not be universal.

Casting antireflective coating (ARC) onto the back side of the glass substrate of PSCs is a simple and practical

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light-management method to increase photon entry into the photoactive layers, and thereby enhances the efficiency of photovoltaics [16]. Mesoporous silica nanoparticles (MSNs) have been widely employed as antireflective materials due to its low refractive index (<1.2). Although a single layer ARC could be simply casted by spin-coating the MSN suspension [17,18], the transmittance is limited by the angle and wavelength range of the incident light [19–21]. To minimize light reflection in a broadband or even full wavelength range, multilayer ARCs and structured ARCs having graded refractive indices have been explored [21]. For example, polydimethylsiloxane (PDMS) nanocone ARC coated on flexible PSCs has been reported to increase the PCE from 12.04% to 13.14% [22]. Inverted micro-pyramidal structured PDMS ARC, achieving 95.2% transmittance of the glass, improved the PCE of $\text{CH}_3\text{NH}_3\text{PbI}_3$ -based PSCs from 17.17% to 17.74% [23]. Here, the size of the PDMS nanocones and the spacing between each other should be precisely controlled, which is challenging. Trilayer ARC made by solution method can achieve nearly full-transmittance in the visible region [24–26]. Lien *et al.* [27] reported an increased efficiency of monocrystalline Si solar cells by 39% after coating a trilayer ARC $\text{SiO}_2/\text{SiO}_2\text{-TiO}_2/\text{TiO}_2$. This trilayer ARC, however, requests high temperature heating of each spin-coated layer, and is therefore not suitable for perovskite which will decompose under those treatments.

Bilayer ARCs, consisting of a lower-refractive-index layer and a higher-refractive-index layer, have more simplified manufacturing process compared with the trilayer ARCs and superior to the single-layer ARC for achieving antireflection over a broadband range if the refractive indices and thicknesses of the two layers can be rationally designed. For instance, Kantarli *et al.* [28] fabricated ARCs by vacuum evaporation on silicon and reported that the double-layer ARC (MgF_2/ZnS) can produce low reflectance in a broader region than that achieved *via* a single-layer ARC made of SiO_2 , CeO_2 or ZnS . Li *et al.* [29] reported a bilayer silica ARC, with nearly full transmittance could be achieved in the wavelength range from 500 to 850 nm. Prené *et al.* [30] showed that nearly full transmittance between 550 and 850 nm could be achieved by adjusting the refractive indices of the bottom Ta_2O_5 and top SiO_2 layers.

In this study, a bilayer ARC was prepared by spin-coating in air with low-temperature post-treatment and applied as ARC for PSCs to increase light absorption and device efficiency. The refractive index and thickness of the bottom layer made from silica polymer are 1.42 and

ca. 95 nm, respectively. The top layer is made from a mixture of hexamethyldisiloxane-modified MSNs (HMDS-MSNs) [17] and a fluorinated silica polymer. The refractive index and thickness of the top layer are 1.21 and ca. 115 nm, respectively. With the controlled refractive indices and thicknesses, the bilayer ARC could increase the transmittance of the PSCs' glass substrate from ca. 90% to over 95% in the range from 488 to 745 nm, and features improved surface hydrophilicity enabled by the fluorinated silica polymer in the ARC2 layer to provide environmental durability. The bilayer ARC was solution-coated on the light incidence side of the glass substrate after the fabrication of PSCs, therefore has no interference to the fabrication of the PSCs. The short-circuit density (J_{sc}) and PCE of the $(\text{FAPbI}_3)_x\text{-(MAPbBr}_3)_{1-x}$ PSCs could be enhanced from 25.5 mA cm^{-2} and 22.7% to 26.5 mA cm^{-2} and 23.9%. The bilayer ARC demonstrated in this work can be applied to other photovoltaic devices, e.g., organic solar cells and quantum-dot solar cells, to improve light absorption of the photoactive layer and consequently enhance the photovoltaic performance.

EXPERIMENTAL SECTION

Materials

Tetraethyl orthosilicate (TEOS, >99%) was purchased from Macklin. Triethanolamine (TEA, AR), hydrochloric acid (HCl, 36%~38%), ethanol, iso-propanol, dimethyl sulfoxide (DMSO) and dimethyl formamide (DMF) were purchased from Shenshi Chemical China. 4-*tert*-Butylpyridine (TBP), bistrifluoromethanesulfonimide lithium salt (Li-TFSI), 1H,1H,2H,2H-perfluoroalkyltriethoxysilanes, HMDS (99%) and hexadecyltrimethylammonium bromide (CTAB, 99%) were purchased from Aladdin. Thiourea, $\text{SnCl}_2 \cdot 2\text{H}_2\text{O}$, PbI_2 , $\text{CH}_3\text{NH}_3\text{Cl}$ (MACl), $\text{CH}(\text{NH}_2)_2\text{I}$ (FAI), and $\text{CH}_3\text{NH}_3\text{Br}$ (MABr) were purchased from Sigma Aldrich. SnO_2 quantum dot solution was synthesized as reported [31].

Synthesis and preparation of antireflective coatings

The silica polymer used to spin-cast the antireflective coating one (ARC1) was synthesized by the reaction of 200 μL of TEOS and 50 μL of HCl (0.1 mol/L) in 2 mL of 2-propanol at room temperature for 2 h. The fluorinated silica polymer was synthesized with the above method as well, but with 1H,1H,2H,2H-perfluoroalkyltriethoxysilanes replacing TEOS. The HMDS-MSN suspension was synthesized as reported in our previous study [17]. Here, the HMDS-MSN suspension was blended with the

fluorinated silica polymer to spin-cast the antireflective coating two (ARC2). The bilayer ARC film was fabricated by spin-coating the as-synthesized solutions in air. The solid concentration of the solutions was adjusted to vary the film thickness which was determined by a spectroscopy ellipsometer (SE) (M2000D, J. A. Woollam Co.). The spin-cast ARC1 layer was heated at 50°C for 30 s to ensure its complete dry before coating the second layer ARC2. The mixture solution of HMDS-MSNs/fluorinated silica polymer is made up of 2.5 wt% HMDS-MSNs and 6.75 wt% fluorinated silica polymer, both in 2-propanol and with a volume ratio of 2:1. The surface structures of the ARC1 and ARC2 were characterized by scanning probe microscopy (SPM) (Solver NEXT, NT-MDT) and scanning electron microscopy (SEM) (S4800, Hitachi).

Optical modeling

The TFCalc software was used to fit and analyze the transmittance and reflectance of the glass coated with ARC2 or bilayer ARC. Optical parameters of ARCs, including refractive index and extinction coefficient were measured using SE and analyzed with the Cauchy mode. Other parameters that were added in the optical modeling are shown in Table 1.

Fabrication of the PSCs

The architecture of the $(\text{FAPbI}_3)_x(\text{MAPbBr}_3)_{1-x}$ PSCs from bottom to top is indium tin oxide (ITO) as the cathode, SnO_2 layer as the electron transport layer, fullerene dimer (NMBF-Cl dimer) as the interfacial layer, $(\text{FAPbI}_3)_x(\text{MAPbBr}_3)_{1-x}$ hybrid perovskite as the photoactive layer, doped spiro-OMeTAD as the hole transport layer and Ag as the electrode. The fabrication procedures are described herein. After sonication in deionized water, ethanol and isopropyl alcohol in sequence for 10 min each, the pre-patterned ITO glass substrates (resistance ca. 15 Ω per square) were dried at 100°C on a hotplate and subsequently treated with UV/Ozone for 15 min. Then the SnO_2 quantum dot solution was spin-coated onto the ITO glass at a speed of 3000 rpm for 30 s and annealed at 200°C for 60 min, and subsequently treated with UV/Ozone for 10 min. A layer of NMBF-Cl dimer was spin-coated on top of SnO_2 as an interfacial layer.

The PbI_2 solution (642.6 mg dissolved in the mixture of 940 μL of DMF and 60 μL of DMSO) was stirred at 60°C on a hotplate until thorough dissolution. The perovskite precursors, FAI, MABr and MACl (weight ratio of 80:5:9), were dissolved in 2-propanol with a concentration of 94 mg L^{-1} . The perovskite film was prepared by a two-step method. First, 30 μL of PbI_2 solution was spin-

Table 1 The modeling factors and values

Modeling Factors	Values
Reference wavelength (nm)	550
Illuminant	White
Incident angle (°)	0.0
Incident medium	Air
Substrate	Glass
Thickness (mm)	1.0
Exit medium	Air
Detector	Ideal
First surface	Front

coated at a speed of 2000 rpm for 30 s, and then annealed at 70°C for 1 min. After cooling to room temperature, 50 μL of the mixture of FAI, MABr and MACl was spin-coated on the PbI_2 film at a speed of 2200 rpm for 15 s. The above fabrication was performed in a nitrogen-filled glovebox. Subsequently, the films were taken into 40% humidity air and annealed at 150°C for 15 min. Finally, smooth and black perovskite films were obtained.

To prepare the spiro-OMeTAD hole transport layer, 17.5 μL of Li-TFSI acetonitrile solution (520 mg mL^{-1}) and 28.5 μL of TBP as dopants were firstly added into 1 mL of spiro-OMeTAD solution (80 mg mL^{-1}). The mixture was spin-coated on the perovskite layer at a speed of 4000 rpm for 30 s. After 16-h oxidation in a glass dryer, the Ag electrode was thermally evaporated onto the hole transport layer under high vacuum through the shadow mask. Each device consisted of 8 pixels, and the size of each pixel, determined by the anode and cathode, was 4 mm². Finally, all PSC devices without any encapsulation were moved out of the glovebox for current density-voltage (J - V) and external quantum efficiency (EQE) measurements. Specifically, the J - V characterization was performed under AM 1.5G (100 mW cm^{-2}) employing a Newport 3A solar simulator (Newport, USA) and a source meter unit (2612B, Keithley, USA) with a J - V scanning software (Ossila Ltd., UK), which was further calibrated with an NREL-certified silicon reference cell before the measurement. The devices were masked with a metal aperture mask to accurately define the testing area on each pixel, and to eliminate the influence of stray and wave guided light. EQE employed an EQE system (Zolix, China) with the monochromatic beam generated from a 150-W xenon lamp. The bilayer ARC was coated on the outside of the glass substrate after the fabrication of PSC, and device performance was tested before and after the coating of the bilayer ARC for comparison.

RESULTS AND DISCUSSION

The synthesis of HMDS-MSNs, as schemed in Fig. 1a, follows our previous report [17]. The syntheses of silica polymer and fluorinated silica polymer are described in the experimental section and outlined in Fig. 1b, c. The bilayer ARC, coated on the back side of PSCs (see Fig. 1d), consists of ARC1 prepared by spin-coating the silica polymer solution, and ARC2 prepared by spin-coating the mixture of the fluorinated silica polymer and HMDS-MSNs.

The surface structures of the ARC1 and ARC2 probed by SPM and SEM are shown in Fig. 2. The ARC1 made from the silica polymer is smooth and flat, as evidenced by the SEM image (Fig. 2d) and especially the SPM image in Fig. 2a having a root mean square (RMS) surface roughness of 0.3 nm only. The ARC2 layer made from the mixture of HMDS-MSNs and the fluorinated silica polymer was spin-coated on bare glass and ARC1, respectively, and their SPM images are shown in Fig. 2b, c. Marginal difference could be identified from the two images, with the RMS of ARC2 coated on glass and ARC1

around 25 nm, close to the average particle size of around 25 nm of HMDS-MSNs. The underneath ARC1 therefore will not affect the film formation of the ARC2, but promote the adhesion between ARC2 and the glass to enhance the mechanical durability of the bilayer ARC, since ARC1 has a relatively low glass transition temperature compared with ARC2. The roughness of bilayer ARC layer is far less than the visible wavelength and will not cause serious light scattering. Compared with the ARC prepared with the mixture of HMDS-MSNs and silica polymer in our previous study [17], the bilayer ARC here has increased hydrophobicity due to the fluorinated silica polymer. The water contact angle (WCA) image of the bilayer ARC is shown as inset in Fig. 2e, and a high WCA of 133° (compared with a WCA of 12° for the ARC1 layer only) ensures a good environmental durability of this bilayer ARC.

In a single-layer design for ARC, the refractive index of ARC should meet $n_{\text{arc}} = \sqrt{n_{\text{air}} n_{\text{s}}}$, where n_{arc} , n_{air} and n_{s} are the refractive indices of ARC, air and substrate, re-

Figure 1 The synthesis routes of (a) HMDS-MSNs, (b) silica polymer and (c) fluorinated silica polymer, and (d) the device architecture of the PSCs coated with the bilayer ARC.

Figure 2 SPM images of the (a) ARC1 layer, (b) ARC2 layer coated on glass and (c) ARC2 layer coated on ARC1. SPM image sizes are $5\ \mu\text{m} \times 5\ \mu\text{m}$. SEM images of (d) ARC1 layer and (e) ARC2 layer coated on ARC1. The insets in (d) and (e) show the water contact angle images of ARC1 and ARC2 coated on ARC1.

spectively [17]. The refractive index of ARC2 almost meets this equation and therefore shows an antireflective effect in a relatively narrow range around 550 nm, as evidenced by our experimental measurement shown in Fig. 3a. However, the transmittance of the single ARC2 layer coated on glass reduces in the short-wavelength range and especially in the long-wavelength range. Accordingly, the reflectance of the single ARC2 layer is high in both the short- and long-wavelength ranges, as shown in Fig. 3b. This marks the advantage as well as limit of single layer design of ARC to enhance the light absorption and solar cell efficiency, as demonstrated in our previous study on organic solar cells [17].

According to the theory of ARC on a low-index substrate [32], the refractive index of ARC1 (n_1) and ARC2 (n_2) should meet $n_2 = n_1 \sqrt{n_{\text{air}}/n_s}$, and the optical thickness of each layer should be around a quarter of the center wavelength (550 nm) of the incident light, i.e., $\lambda/4$, to enable a broadband antireflective effect of the bilayer ARC [29,33]. The refractive indices of ARC1 and ARC2 are 1.42 and 1.21, respectively, according to the SE measurements, which satisfy the above equation. The above refractive indices also set the physical thickness of ARC1 and ARC2 to be around 95 and 115 nm, respectively. The solid contents of each ARC solution and the

spin speed should be tuned to receive the targeted film coating with a wide window of solid content or spin speed existing to offer flexibility.

Once the refractive index and thickness of each ARC layer have been tuned to optimize light transmittance, the antireflective effect of the bilayer ARC in a broader wavelength can be achieved. Fig. 3a, b show that the bilayer ARC can significantly increase the transmittance (or reduce the reflectance) of glass in a broader wavelength range than the effect of a single-layer ARC2. The max transmittance of the glass coated with the bilayer ARC is over 95% at 550 nm, and remains high in both short- and long-wavelength ranges. The reason for not achieving the full transmittance or zero reflectance is that the bilayer ARC is coated on one side rather than both sides of the glass [34]. We also employed software TFCalc [24,25,35] to calculate the transmittance and reflectance of the glass coated with the bilayer ARC to verify our experimental results. The refractive index and thickness obtained by SE measurements were introduced into the model to start the calculation. The details of modeling parameters are shown in Table 1. As shown in Fig. 3a, b, the model fitted results match relatively well with our experimental results, although minor deviations between modeling and experiment can be observed. The main reason is that the

Figure 3 (a) Transmittance and (b) reflectance of the glass, glass coated with the single-layer ARC2 and bilayer ARC. (c) Transmittance of the fresh bilayer ARC and that after 3 month aging.

absorptions of glass and bilayer ARC have not been considered in the TFCalc calculation. As an examination of the environmental durability of the bilayer ARC, the transmittance of the glass coated with the bilayer ARC was measured again after 3 month aging and marginal reduction can be found in Fig. 3c, suggesting good durability in air.

The bilayer ARC was then coated on the outside of the glass substrates of PCs (see device architecture in Fig. 1d), with $(\text{FAPbI}_3)_x(\text{MAPbBr}_3)_{1-x}$ hybrid perovskite as the light absorber. Each PSC fabricated on a single glass substrate was pixelated to eight individual sub-devices, each of which can operate separately and therefore can be employed to evaluate the uniformity of bilayer ARC at different locations of a glass substrate. All PSCs before and after coating with the bilayer ARC were measured under simulated one sun with a light intensity of 100 mW cm^{-2} . Representative J - V curves of $(\text{FAPbI}_3)_x(\text{MAPbBr}_3)_{1-x}$ PSCs are plotted in Fig. 4a, and the average and maximum photovoltaic parameters (J_{SC} , fill factor (FF), V_{OC} and PCE) are summarized in Table 2. The reference device without the bilayer ARC delivers a maximum PCE of 22.7%, with an average J_{SC} of $25.3 \pm 0.3 \text{ mA cm}^{-2}$, FF of $75.8 \pm 4.1\%$, V_{OC} of $1.07 \pm 0.04 \text{ V}$ and PCE of $20.5 \pm 1.6\%$. This decent device performance is due to the strong light absorption of the $(\text{FAPbI}_3)_x(\text{MAPbBr}_3)_{1-x}$ hybrid perovskite, and is hysteresis-free benefiting from the dual defect-passivation function of the NMBF-Cl dimer interlayer to both SnO_2 and perovskite layer, as reported in our recent study [36]. With the bilayer ARC, the average J_{SC} of PSCs is enhanced to $26.3 \pm 0.3 \text{ mA cm}^{-2}$, with the FF and V_{OC} almost unchanged, resulting in an average PCE of $21.6 \pm 1.6\%$ with a maximum of 23.9%. The enhanced J_{SC} of PSC is due to the improved light absorption of the perovskite layer for

the antireflective effect of the bilayer ARC in a broadband wavelength (see Fig. 3a), supported by the EQE spectra presented in Fig. 4b. The intensity of the EQE spectrum is enhanced in the wavelength range from 300 to 800 nm, indicating the enhanced photon to electricity conversion. The calculated J_{SC} from the integration of the EQE spectra is also summarized in Table 2, which are found about 7% less than the J_{SC} obtained from the J - V curves. This discrepancy is an intrinsic result of the difference between the illumination conditions, as EQE measurement employs monochromatic light at a single wavelength, while J - V sweep employs simulated full spectrum sun light [37].

The photovoltaic parameters of all eight pixels sharing the same ITO glass are plotted in Fig. 4c-f. Compared with the PSC without the bilayer ARC, enhanced J_{SC} on all eight pixels can be observed, with the FF and V_{OC} almost unchanged. The ARC layer is coated outside of the PSC and will not interfere with the photon to electricity conversion process of PSCs, except allowing more photons to reach the perovskite layer and be absorbed. The average J_{SC} increment is about 4%, and is close to the transmittance improvements shown in Fig. 3a. The testing of performance on different pixels of device fabricated on a single glass substrate demonstrates the uniformity of these solution-processed ARCs and high reproducibility of enhancing device efficiency. Our low-cost, solution-processed bilayer ARC locates on the back side of the glass substrate, and therefore does not interfere with the fabrication of the solar cells and can be applied to any type of solar cells, e.g., organic solar cells, PSCs, silicon solar cells and CIGS solar cells, thereby holding promising commercialization potential.

CONCLUSIONS

A bilayer ARC has been designed, with the bottom layer

Figure 4 (a) *J*-*V* curves and EQE spectra of the (FAPbI₃)_x(MAPbBr₃)_{1-x} PSCs coated with and without the bilayer ARC. (c) PCE, (d) *J*_{sc}, (e) FF and (f) *V*_{oc} of all eight pixels of a (FAPbI₃)_x(MAPbBr₃)_{1-x} PSC with and without the bilayer ARC.

Table 2 Device metrics of the PSCs with and without the bilayer ARC

	<i>J</i> _{sc} (mA cm ⁻²)	Calculated <i>J</i> _{sc} (mA cm ⁻²)	FF (%)	<i>V</i> _{oc} (V)	PCE (%)
(FAPbI ₃) _x (MAPbBr ₃) _{1-x} (W/O ARC)	25.5 (25.3±0.3)	23.7	80.5 (75.8±4.1)	1.11 (1.07±0.04)	22.7 (20.5±1.6)
(FAPbI ₃) _x (MAPbBr ₃) _{1-x} (with bilayer ARC)	26.5 (26.3±0.3)	24.8	80.5 (76.2±3.8)	1.12 (1.07±0.04)	23.9 (21.6±1.6)

made from a silica polymer and the top layer made from the mixture of HMDS-MSNs and a fluorinated silica polymer. By tuning the refractive index and film thickness of each layer, a bilayer ARC with enhanced transmittance of the glass in a broadband wavelength range has been prepared, with the maximum transmittance being increased from ca. 90% to 95%. The bilayer ARC

was coated on the outside of the glass substrate of PSCs, and found to increase the *J*_{sc} about 4%, resulting in an increased maximum (uncertified) PCE from 22.7% to 23.9% of the solar cells with a device structure of glass/ITO/SnO₂/fullerene/(FAPbI₃)_x(MAPbBr₃)_{1-x}/Spiro-OMeTAD/Ag. This work presents a simple yet effective strategy to enhance the efficiency of photovoltaic solar

cells *via* the light management approach through employing bilayer ARCs.

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Author contributions Wang Y synthesized and prepared the ARC coating. Wang H, Chen M and Wang P fabricated the solar cell devices. Mao Y and Han W characterized the film morphology. Liu D and Wang T conceived the idea. All authors discussed the results and approved the manuscript.

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宽波段减反膜实现23.9%效率的平面异质结构钙钛矿太阳能电池

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摘要 虽然钙钛矿太阳能电池效率的发展令人鼓舞,但是由于光反射造成的器件基底界面的光子损失等问题仍然没有解决. 光管理是降低反射损失并提高器件效率的有效途径. 因此,我们设计了双层减反膜以涂敷在 $(\text{FAPbI}_3)_x(\text{MAPbBr}_3)_{1-x}$ 钙钛矿太阳能电池的玻璃基底外侧,以期达到增加光吸收和提高器件效率的目的. 该研究中的减反膜底层由硅聚合物构成,上层由氟代硅聚合物和六甲基二硅氧烷/介孔二氧化硅纳米粒子复合而成. 通过精确调控上下层的折射率及厚度,我们在宽波段范围内实现了玻璃基底透过率从最高约90%显著提升到95%. 在电池器件的玻璃基底外侧溶液涂膜制备减反膜后, $(\text{FAPbI}_3)_x(\text{MAPbBr}_3)_{1-x}$ 钙钛矿太阳能电池在保持填充因子和开路电压不变的情况下,短路电流和效率分别从 25.5 mA cm^{-2} 和 22.7% 提高到 26.5 mA cm^{-2} 和 23.9%. 本研究提出了一种简单、高效的通过双层减反膜的光管理提高太阳能电池效率的方法,且此方法可拓展到其他类型太阳能电池体系.