

Tailoring the Interface in FAPbI₃ Planar Perovskite Solar Cells by Imidazole-Graphene-Quantum-Dots

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Organic–inorganic hybrid perovskites have reached an unprecedented high efficiency in photovoltaic applications, which makes the commercialization of perovskite solar cells (PSCs) possible. In the past several years, particular attention has been paid to the stability of PSC devices, which is a critical issue for becoming a practical photovoltaic technology. In particular, the interface-induced degradation of perovskites should be the dominant factor causing poor stability. Here, imidazole bromide functionalized graphene quantum dots (I-GQDs) are demonstrated to regulate the interface between the electron transport layer (ETL) and formamidinium lead iodide (FAPbI₃) perovskite layer. The incorporation of I-GQDs not only reduces the interface defects for achieving a better energy level alignment between ETL and perovskite, but also improves the film quality of FAPbI₃ perovskite including enlarged grain size, lower trap density, and a longer carrier lifetime. Consequently, the planar FAPbI₃ PSCs with I-GQDs regulation achieve a high efficiency of 22.37% with enhanced long-term stability.

1. Introduction

Perovskite solar cells (PSCs) have been the front runner among the emerging next-generation photovoltaic technologies because of the high power conversion efficiency (PCE) and low-cost solution-based processing approaches.^[1–3] However, the current PSCs are still facing poor device stability, which will have a decisive impact on the commercialization of PSCs.^[4,5] The assaults of moisture, oxygen, heat, and light have been identified as the inducement to activate degradation of perovskite.^[6–8] To address this issue, the composition optimization and additives incorporation have been investi-

gated for improving the intrinsic stability of perovskite under different stimuli.^[9–12] Moreover, numerous effective strategies have been reported to passivate the surface defects of top region of perovskite interconnecting with the carrier transport layer (CTL), and thus to enhance the stability and performance of PSCs.^[6,13,14] Meanwhile, the bottom interface also plays a critical role in the degradation of perovskite active layer and PSC performance and stability.^[15–17]

In particular, in an n-i-p regular architecture PSCs with tin oxide (SnO₂) as ETL, the numerous surface traps in low-temperature solution-processed SnO₂ not only influence the crystallization and thus quality of perovskites, but also increase non-radiative recombination losses and reduce PSC performances.^[18–21] Hence, it is imperative to develop feasible bottom

interface modification methods for tailoring the interface defects and stability.

In this work, we first propose to use the novel imidazole bromide functionalized graphene quantum dots (I-GQDs) for tailoring the interface between SnO₂ ETL and FAPbI₃ perovskite. The multifunctional functional groups on the surface of GQDs could reduce the interface trap states and enhance the quality and stability of PSCs, inhibiting non-radiative recombination. Simultaneously, the incorporation of I-GQDs could improve the conductivity of ETL and acquire a better energy level alignment, which improves interface carrier transfer. As a consequence, the formamidinium lead iodide (FAPbI₃) based PSCs with I-GQDs interface modification achieve a very high PCE of 22.37% and prolonged operational stability.

2. Results and Discussions

Figure S1, Supporting Information shows the schematic diagram of the imidazole modified GQDs. From the high-resolution transmission electron microscopy (TEM) image of the I-GQDs (Figure 1a), the I-GQDs show a narrow size distribution which is close to 10 nm. After spin-coating the SnO₂ ETL, the I-GQDs interface modification layer was prepared by spin-coating the I-GQDs aqueous dispersion with different concentrations (details as shown in the Section 4). By comparing the PSCs with different content I-GQDs interface modification, the

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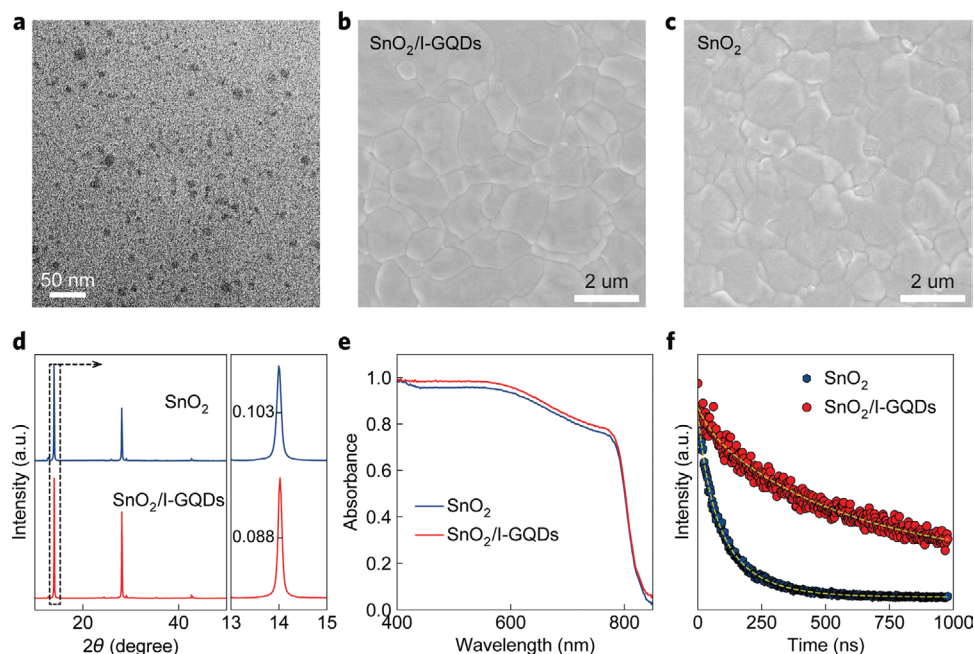


Figure 1. a) TEM image of the I-GQDs. b) The SEM image of perovskite film deposited on the $\text{SnO}_2/\text{I-GQDs}$. c) The SEM image of perovskite film deposited on the pristine SnO_2 film. d) XRD patterns of different SnO_2 substrates-based perovskite films with or without I-GQDs. e) UV-vis spectra of different SnO_2 substrates-based perovskite films. f) The TRPL spectra of different SnO_2 substrates-based perovskite films.

optimal concentration of I-GQDs is confirmed as the 1 mg mL^{-1} (Figure S2, Supporting Information), which is the basis for all subsequent discussions.

Figure S3, Supporting Information presents the transmission of the $\text{SnO}_2/\text{I-GQDs}$ compared with the pure SnO_2 . The modification of I-GQDs would not affect the transmittance of the electron transport layer to visible light. Further analysis of UV-visible (UV-vis) diffused reflectance spectra showed almost the same absorption (Figure S4a, Supporting Information) and optical band gap (Figure S4b, Supporting Information). As a member of the carbon material family, the GQDs possess excellent conductivity, which can improve the electronic properties of SnO_2 -based ETL. The electron mobility of ETL was measured using the space charge-limited current (SCLC) method.^[20,22] Based on the results in Figure S5, Supporting Information and the equation in the Section 4, the electron mobility of $\text{SnO}_2/\text{I-GQDs}$ film is $1.72\times$ that of the pristine SnO_2 film. The remarkable increase of electron mobility demonstrates that the I-GQDs incorporation potentially promote the electron transport property of the ETL.

The morphology of ETL was further characterized by the scanning electron microscope (SEM) and atomic force microscopy (AFM). The indium tin oxide (ITO) substrate was well covered by the SnO_2 or $\text{SnO}_2/\text{I-GQDs}$ films without notable pinholes (Figure S6, Supporting Information). The element energy dispersive spectroscopy (EDS) mapping of N and Br, which are the typical element of I-GQDs, indicated that I-GQDs are uniformly distributed on the surface of film without aggregation (Figure S6b, Supporting Information). Further AFM images revealed that the $\text{SnO}_2/\text{I-GQDs}$ film is more compact and shows the smaller root-mean-square roughness of 1.06 nm , comparing with 1.38 nm of pristine SnO_2 film, which favors the formation of perovskite film (Figure S7, Supporting Information).

To further identify the I-GQDs modification, we conducted the X-ray photoelectron spectroscopy (XPS) analysis which is a more sophisticated surface analysis technique. Based on the XPS survey spectra (Figure S8, Supporting Information), the typical elements N and Br were confirmed, consistent with the result of EDS, examining the existence of I-GQDs on the SnO_2 surface. The Br 3d signal confirmed the existence of Br anions (Figure S9a, Supporting Information). The N XPS spectrum presented the $-\text{NH}-$ (399.5 eV) and nitrogen atoms of the imidazole ring (400.9 eV), referring to Figure S1a, Supporting Information for the structure (Figure S9b, Supporting Information). Besides, the Sn 3d core-level spectra predominantly showed the blue shift to high binding energy for SnO_2 with I-GQDs incorporation (Figure S10, Supporting Information), indicating the electron transfer to tin atoms at the surface, which could effectively eliminate numerous traps in the low-temperature solution-processed SnO_2 .^[23]

The FAPbI_3 ($\text{FA}^+ = \text{formamidinium} = \text{CH}(\text{NH}_2)_2^+$) perovskite layer was deposited on the SnO_2 -based ETLs (see Section 4). Figure 1b,c shows the morphology of the perovskite films deposited on $\text{SnO}_2/\text{I-GQDs}$ and pristine SnO_2 ETL, respectively. Both of FAPbI_3 perovskite thin films are compact, pinhole-free, and full-coverage. However, the FAPbI_3 on the I-GQDs/ SnO_2 show larger grain than that deposited on the pure SnO_2 , as shown in Figure S11, Supporting Information. But for the sample with the incorporation of pure GQDs without imidazole functional groups (Figure S12a, Supporting Information), the grain size of perovskite film is similar to that of perovskite deposited pristine SnO_2 film, which indicates that the imidazole groups contribute to better perovskite film. The time-resolved photoluminescence measurement (TRPL) spectrum of SnO_2/GQDs substrates-based perovskite films with the

laser incident from the ITO side shows reduced charge carrier lifetime (Figure S12b, Supporting Information). It indicates that the addition of GQDs is beneficial to the charge carrier extraction. The X-ray diffraction (XRD) patterns of prepared perovskite films present two peaks characteristic at 14.3° and 28.6° , which assigned to the (001) and (002) crystal planes of α -FAPbI₃ phase, respectively (Figure 1d).^[24] The intensity of XRD peaks for the FAPbI₃/I-GQDs/SnO₂/thin film is stronger than that for the pure FAPbI₃/SnO₂ perovskite, suggesting that the I-GQDs incorporation impact the crystallization and enhances the overall crystallinity of the thin film.

The UV–vis absorption spectra Figure 1e showed that the I-GQDs incorporation has a negligible effect on the UV–vis spectra of the FAPbI₃ perovskite films. The absorbance edges of both thin films are located at ~ 830 , which is consistent with previous results. Furthermore, the optical bandgap of the perovskite films was obtained to be the same as ~ 1.49 eV from their corresponding Tauc plots derived from the UV–vis diffused reflectance absorption spectra (Figure S13, Supporting Information). The steady-state photoluminescence (PL) spectra revealed that the perovskite films showed the same 807 nm photoluminescence peak without obvious deviation from the absorption edge (Figure S14, Supporting Information). Additionally, the perovskite deposited on the SnO₂/I-GQDs ETL showed a stronger PL intensity than that deposited on pristine SnO₂, demonstrating the better quality of the perovskite film on SnO₂/I-GQDs ETL. This is also supported by time-resolved PL measurement with the laser light incident from the perovskite side. This means that the PL decay is dominated by the photo-generated carrier recombination dynamics in the perovskite (Figure 1f).^[25] The SnO₂/I-GQDs/perovskite sample shows a much longer carrier lifetime according to the biexponential fitting results (see the Section 4 and Table S1, Supporting Information), determining comparatively low non-radiative recombination of the perovskite film.

Along with the valence band maximum (VBM) of perovskite and ETLs (Figure S15, Supporting Information), the energy level diagram was obtained. A better band alignment was achieved with I-GQDs modification to reduce charge accumulation and promote electron transfer at the interface (Figure 2a). In general, as an interface layer between SnO₂ and perovskite, I-GQDs not only modify the SnO₂ ETL by improving conductivity, reducing surface defects and adjusting valance band, but also assist the growth of perovskite film and passivate interface defects.

We investigated the PSCs performance based on SnO₂ ETL with and without I-GQDs as ETL (Figure S16, Supporting Information). The current (*J*)–voltage (*V*) characteristics of the champion cells modified with I-GQDs interface layer compared to the controller devices are shown in Figure 2b and Figure S17, Supporting Information. The inserted table summarized the key parameters, including V_{oc} , J_{sc} , fill factor (FF), and PCE. The champion device based on SnO₂ ETL shows a PCE of 19.57% with $J_{sc} = 24.34 \text{ mA cm}^{-2}$, $V_{oc} = 1.031 \text{ V}$, and $FF = 0.78$. In comparison, with the I-GQDs incorporation, the J_{sc} , V_{oc} , and FF are increased to 25.42 mA cm^{-2} , 1.073 V , and 0.82 , yielding a PCE up to 22.37%. The higher J_{sc} and FF are attributed to improved electron extraction and transport. The larger V_{oc} is due to the better energy level and slower charge carrier recombination at

the interface. The obtained PCE distributions with different ETLs are shown in Figure 2c based on twenty devices.

Figure S18, Supporting Information shows the corresponding curves at the maximum power point in the *J*–*V* plots. The PCEs of the champion devices using the SnO₂ and SnO₂/I-GQDs stabilize at 18.09% and 21.07% with photocurrent densities of 21.33 and 22.52 mA cm^{-2} , respectively, very close to the values measured from the *J*–*V* curves. Figure 2d shows the corresponding external quantum efficiency (EQE) spectra of these champion devices with an integrated current density of 23.43 mA cm^{-2} for pristine SnO₂ device and 24.82 mA cm^{-2} for SnO₂/I-GQDs device, respectively, which are highly consistent with the *J*–*V* results.

To evaluate the effects of the interface modification with I-GQDs on the long-term device stability, we recorded the operational stability of the PSCs by exposing unsealed devices at room temperature to full-sun illumination in a nitrogen gas glove box (Figure 2e). After 600 h, the device with the SnO₂/I-GQDs ETL retained over 84% of its initial efficiency, proving excellent operational stability. In comparison, devices with pristine SnO₂ ETL retained merely 51% of their initial efficiency.

To locate the distribution of the I-GQDs, time of flight secondary ion mass spectrometry (ToF-SIMS) measurement was employed. As shown in Figure S19, Supporting Information, the depth profile concentration of typical Br[−] of IGQDs shows the distribution at the interface clearly. The imidazole groups on the surface of I-GQDs helped to improve stability by strong interaction with perovskite,^[11] which may be a factor in how the I-GQDs interface layer could help form high-quality perovskite film. The Br[−] signal could be observed to shift towards the perovskite layer, nearly across the perovskite layer. This diffusion of Br[−] may result from the annealing treatment after spin-coating the perovskite precursor. The 3D depth profile of Br anions gives more distinct evidence for this phenomenon (Figure 3a). In the Pb 4f spectrum (Figure S20, Supporting Information), the Pb peaks shift toward higher binding energy, which is evidence for the formation of stronger ionic bonding between Pb²⁺ and Br[−].^[26] The incorporation of bromine anions may be a benefit to suppresses low-energy rotations of formamidinium (FA) and leads to a longer-lived carrier lifetime,^[27] which is agree with the TRPL results of the perovskite films.

In order to gain insight into the charge transport mechanism, the perovskite devices were also characterized by light intensity (*I*) dependent photovoltage (V_{oc}) and photocurrent short-circuit current density (J_{sc}). There is a linear relationship between J_{sc} and *I*, which elucidates the effective carrier transport and the negligible bimolecular recombination in both devices (Figure S21a, Supporting Information).^[28] In addition, the ideality factor could be evaluated by testing the dependence of V_{oc} on the incident light intensity (Figure S21b, Supporting Information), which could reflect the trap-assisted nonradiative recombination.^[29] Here, the device with the SnO₂/I-GQDs ETL exhibits a slightly lower slope ($1.21 \text{ kT}/q$) than that with the SnO₂ ETL ($1.64 \text{ kT}/q$), which means the less trap-assisted recombination, where *k*, *T*, and *q* are Boltzmann's constant, absolute temperature, and elementary charge, respectively. This result is in excellent agreement with the outcome showing the lowest trap density when the perovskite is deposited on SnO₂/I-GQDs.

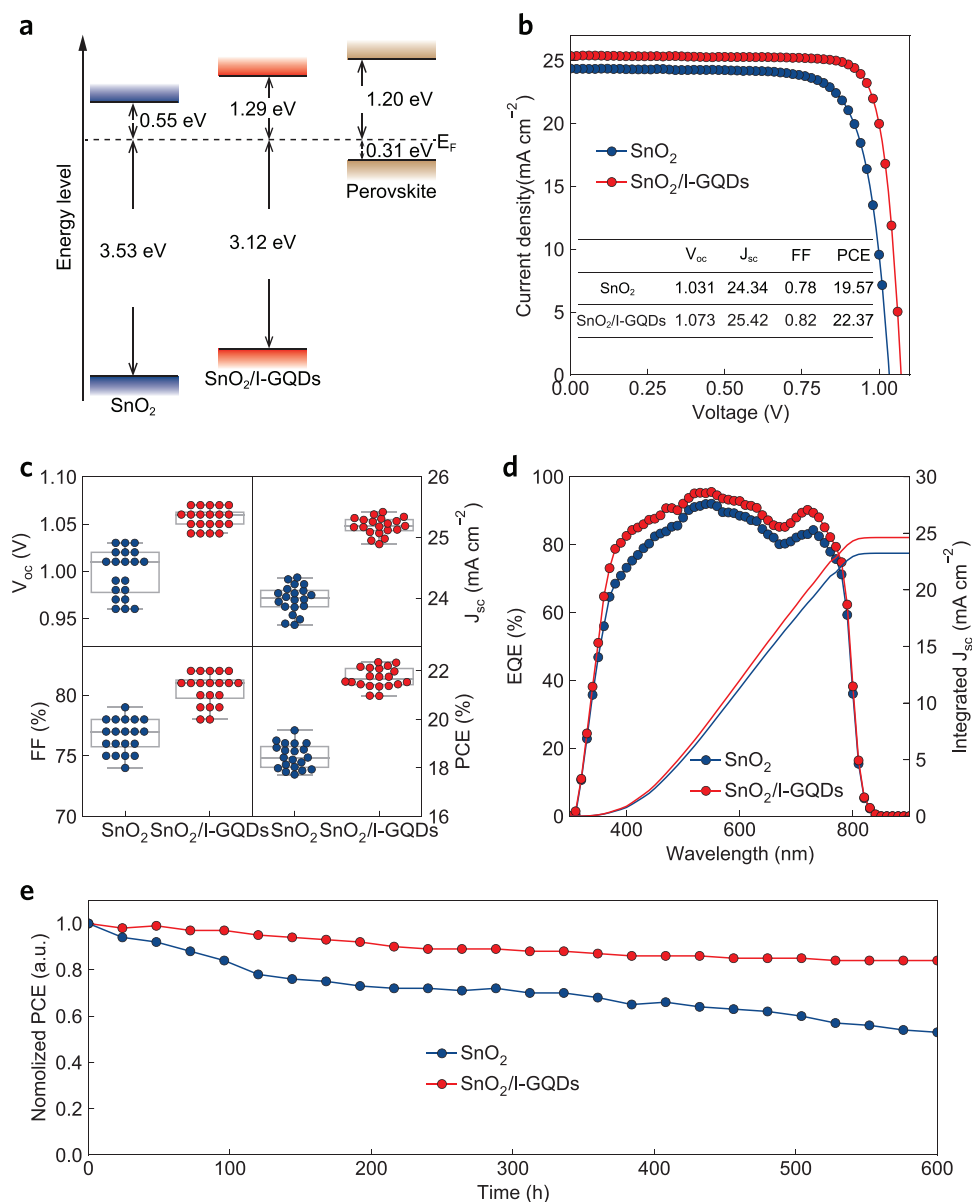


Figure 2. a) Energy level diagram of SnO₂, SnO₂/I-GQDs, and the perovskite layer. b) J-V curves of reversed scan for the SnO₂/I-GQDs-based and pristine SnO₂ devices. c) Efficiency distribution of perovskite solar cells with different SnO₂ ETL. d) EQE spectra and their corresponding integrated J_{sc} of each champion device with different ETL. e) Long-term stability measurements of devices without any encapsulation under an N₂ condition and illumination of 100 mW cm⁻².

Moreover, the carrier recombination rate in the PSCs was evaluated by the transient photovoltage decay technique (Figure 3b). It is apparent that the perovskite devices based on SnO₂/I-GQDs ETL exhibit a slower V_{oc} decay time compared to the devices based on pristine SnO₂ ETL, demonstrating that the devices with SnO₂/I-GQDs have the lower charge recombination rate and the longer carrier lifetime and thus contribute to the higher V_{oc} in J-V characterization.^[18] Meanwhile, the transient photocurrent decay measurement shows the reduced photocurrent decay time, verifying the faster charge transport based on the SnO₂/I-GQDs ETL compared to the pristine SnO₂ ETL (Figure S22, Supporting Information).

In order to further appraise the effect of I-GQDs incorporation on the trap density in the devices, we fabricated the electron-only devices (ITO/ETL/Perovskite/PCBM:C60/Ag) (Figure 3c). The resulted dark current density-voltage curves presented that the devices with I-GQDs showed a 0.21 V of onset voltage for the trap-filled limit (V_{TFL}), which is much smaller than 0.27 V of the sample with pristine SnO₂ film, implying a decreased defect density.

The fast charge collection is also confirmed by the Mott-Schottky (M-S) measurement of perovskite devices. The devices with the SnO₂/I-GQDs ETL demonstrated an increased built-in potential (V_{bi}) of 0.73 V, compared with the devices with the

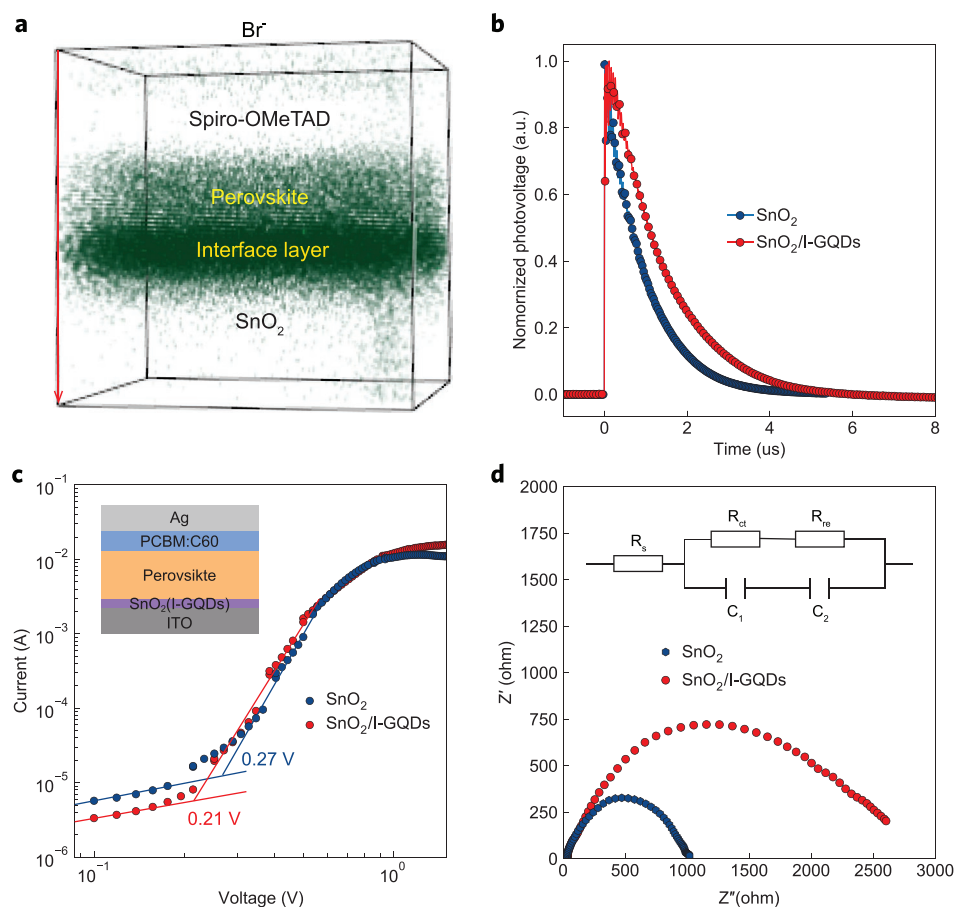


Figure 3. a) Reconstructed elemental 3D maps for the bromine ion traced in the depth profile. b) Normalized transient photovoltage decay curves of the different perovskite solar cell. c) Dark J - V curves of electron-only devices with SnO₂/I-GQDs and SnO₂ ETL. d) Typical Nyquist plots of PSCs with SnO₂/I-GQDs and SnO₂ ETL. The inset shows the equivalent circuit diagram.

pure SnO₂ ETL (0.62 V) (Figure S23, Supporting Information). In further, the electrochemical impedance spectroscopy (EIS) measurement was adopted to reveal the potential carrier transport behaviors in the PSCs. Figure 3d shows the Nyquist plots of the devices with different ETLs with an applied bias voltage of 1.0 V close to the V_{oc} under dark conditions and the inset represents the equivalent circuit. The lower charge transport resistance (R_{ct}) and higher charge recombination resistance

(R_{rec}) in devices with the SnO₂/I-GQDs ETL shows the enhanced charge transport, as well as the reduced recombination.^[30]

In addition, the solar cell devices with different ETLs were tested as the light-emitting diodes (LEDs) in the dark and under forwarding voltage bias. Both two devices with SnO₂ and SnO₂/I-GQDs showed an emission peak located at 808 nm, in good consistent with the emission peak of PL spectra (Figure 4a,b). From Figure 4c, it can be seen that the electroluminescence

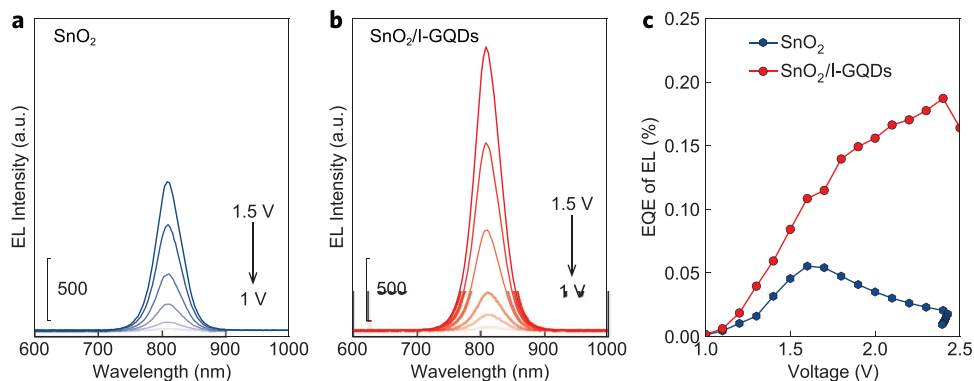


Figure 4. a) EL spectra of the devices with SnO₂ ETL under different voltage bias operating as LEDs. b) EL spectra of the devices with SnO₂/I-GQDs ETL under different voltage bias operating as LEDs. c) EQE of EL of the devices while operating as LEDs.

efficiency of the device with SnO₂/I-GQDs ETL is much higher than that of the device with SnO₂ ETL, which means an improvement V_{oc} for PSCs.^[31] Based on the function of $\frac{k_B T}{q} \ln(EQE_{EL})$, the V_{oc} improvement (ΔV_{oc}) due to the reduction in non-radiative recombination with I-GQDs interface layer can be estimated as 0.031 V by $\Delta V_{oc} = K_B T/q \ln(EQE_{with I-GQDs}/EQE_{without I-GQDs})$ which is almost consistent with the $J-V$ results.

As a result, the modification of I-GQDs will improve the conductivity of SnO₂-based ETL, tune the conductive band level, and fill the traps of the surface of SnO₂, which is conducive to enhance electron transfer and diminish the carrier recombination at the interface between ETL and perovskite. Moreover, the I-GQDs at the bottom interface could promote the formation of high-quality perovskite film, reduce the charge recombination and promote carrier transport, which benefits to improve the efficiency of perovskite solar cells.

3. Conclusions

We introduce the I-GQDs interface layer between SnO₂ ETL and perovskite layer in n-i-p FAPbI₃-based planar-type PSCs to improve their performance and stability. The incorporation of I-GQDs at the interface can improve the conductivity and eliminate surface defects of SnO₂ ETL, achieve a better conduct band alignment to enhance carrier transfer, and inhibit interface charge recombination to reduce the voltage loss. Moreover, the functional groups on the surface of I-GQDs are benefiting to form high-quality perovskite film to reduce nonradiative recombination within the perovskite film and improve the stability of PSCs without changing the band gap of the FA-based perovskite layer. The PSCs with I-GQD interface modification exhibited a PCE of 22.37% for an FA-based perovskite devices. This work provides a facile and efficient interface modification method to improve both the performance and operational stability of FAPbI₃-based perovskite solar cells.

4. Experimental Section

Materials: Dimethylformamide (DMF, 99.8%), dimethyl sulfoxide (DMSO, 99.9%), ethanol, acetone, chlorobenzene (CB, 99.9%), acetonitrile (ACN, 99.8%), 4-tert-butyl pyridine (tBP, 96%), Tris(2-(1H-pyrazol-1-yl)-4-tert-butylpyridine)cobalt(III) tri[bis(trifluoromethane)sulfonimide] (FK 209 Co(III) TFSI, 99.95% trace metals basis) were purchased from Sigma-Aldrich. Lead (II) iodide (PbI₂, 99.999%), SnO₂ colloidal solution (tin (IV) oxide, 15 wt% in H₂O colloidal dispersion) were purchased from Alfa Aesar. I-GQDs and GQDs powder was purchased from Nanjing XFNANO Materials Tech Co., Ltd. Formamidinium iodide (FAI) were purchased from GreatCell Solar (Australia). Methylammonium chloride (MACl) and 2,2',7,7'-Tetrakis[N,N-di(4-methoxyphenyl)amino]-9,9'-spirobifluorene (Spiro-OMeTAD, 99.8%) were purchased from Xi'an Polymer Light Technology in China.

Device Fabrication: The ITO glass substrates were sequentially washed by detergent, deionized water, acetone, and anhydrous ethanol for 20 min, respectively. Then, the ITO glasses were dried by a nitrogen gas gun and treated with Ultraviolet–Ozone (UV–Ozone) for 20 min.

The purchased SnO₂ colloidal dispersion (15 wt%) was first diluted by deionized water (1:6 vol%) and I-GQDs dispersion was prepared by dissolving I-GQDs powder in deionized water with the concentration of 0.5, 1, and 2 mg mL⁻¹, respectively. After that, diluted SnO₂ colloidal dispersion was spin-coated onto the clean ITO glass substrates at 3000 rpm for 30 s, followed by annealing at 150 °C for 30 min in ambient air. For the modification with I-GQDs, the I-GQDs dispersion was spin-coated onto the cooling SnO₂ film at 3000 rpm for 30 s, followed by annealing at 100 °C for 10 min in ambient air. Here, a typical one-step anti-solvent deposition method was adopted to fabricate pure FAPbI₃ perovskite films. In detail, 50 μL of perovskite precursor solution (258 mg FAI, 692 mg PbI₂, and 40 mg MACl were dissolved in 0.9 mL of DMF and 0.1 mL of DMSO mixed solvent) was spin-coated on SnO₂-based ETL at 5000 rpm for 20 s. Fifteen seconds before the end of the procedure, 150 μL chlorobenzene was poured rapidly on the perovskite films. Subsequently, the films were transferred to a hot plate and annealed at 150 °C for 20 min. All of these processes were performed in a dry air glovebox. After cooling down, a Spiro-OMeTAD solution with consists of 72.3 mg Spiro-OMeTAD, 28.8 μL of 4-tert-butyl pyridine, 27.8 μL of FK 209 Co(III) TFSI solution (300 mg of FK 209 in 1 mL of ACN), and 17.5 μL of Li-TFSI solution (520 mg of Li-TFSI in 1 mL of ACN) in 1 mL CB was spin-coated on perovskite films at 4000 rpm for 25 s. Finally, 90 nm of Ag electrode was thermally evaporated under a high vacuum using an E-beam thermal evaporation system.

Characterization: The SEM images and EDS mapping were obtained by Hitachi S-4800 FEG. The TEM image was obtained by FEI Tecnai F20. The XRD was taken using a Bruker D2 Phaser using a Cu Kα. The XPS and VBM were tested on Physical Electronics PHI 5802 with a monochromatic Al Kα X-ray source. The AFM was conducted on NT-MDTNTEGRA with tapping mode. The ToF-SIMS characterization was performed on TOF.SIMS 5 IONTOF.

The steady-state photoluminescence (PL) and time-resolved PL spectra were measured on a PicoQuant FluorTime 300 instrument. A picosecond 375 nm pulse laser (LDH-P-C-75) with a pulse width of <40 ps was used to excite the samples.

The current density–voltage ($J-V$) curves of PSCs were characterized by using a Keithley 2400 source meter and a Newport AM 1.5 G solar simulator under a light intensity of 100 mW cm⁻², calibrated with a standard silicon reference cell. The steady-state PCE was measured at a maximum power point and then tracing the current density. The EQE measurement was performed by a system combining xenon lamp monochromatic chopper, and a lock-in amplifier with a calibrated silicon photodetector (Hamamatsu mono-Si cell).

The stability was tested at an N₂ glove box with illumination of 100 mW cm⁻². The EIS was measured by an electrochemical workstation (Autolab, PGSTAT 302N) under illumination with an alternative signal amplitude of 5 mV and in the frequency range of 800–0.01 kHz. The transient photovoltage and transient photocurrent decay were recorded on a digital oscilloscope (MDO3102, Tektronix, Inc) with a 532 nm 10 ps pulse width laser (5 μJ pulse⁻¹ maximum at 1 MHz) (HE532-5, Fianium).

The space-charge-limited-current (SCLC) method:

$$N_{\text{trap}} = \frac{2\epsilon_0 \epsilon V_{\text{TFL}}}{eL^2} \quad (1)$$

where ϵ_0 is the vacuum permittivity, ϵ of 46.9 for the perovskite is adopted, e is the electron charge, and L is the thickness of the film.

The space-charge-limited-current (SCLC) equation for electron mobility:

$$\mu_e = \frac{8JL^3}{9\epsilon_0 \epsilon (V_{\text{app}} - V_r - V_{\text{bi}})^2} \quad (2)$$

where J is the current density, L is the thickness of ETL, ϵ is the relative dielectric constant of ETL, ϵ_0 is the vacuum permittivity, V_{app} is the applied voltage, V_r is the voltage drop owing to constant resistance and series resistance across the electrodes, V_{bi} is the built-in voltage due to the different the work function of the two electrodes and μ_e is the electron mobility.

The Bi-Exponential Decay Model for TRPL:

$$I(t) = A_1 \exp\left(-\frac{t-t_0}{\tau_1}\right) + A_2 \exp\left(-\frac{t-t_0}{\tau_2}\right) \quad (3)$$

where t_0 is the start time of the decay process, τ_1 and τ_2 represent the first- and second-order decay times, A_1 and A_2 are weighting coefficients of each decay channel.

The average recombination lifetime (τ) is estimated with the A_i and τ_i values from the fitted curve data according to the following equation:

$$\tau = \sum A_i \tau_i^2 / \sum A_i \tau_i \quad (4)$$

Supporting Information

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

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Keywords

imidazole graphene quantum dots, interface regulation, planar perovskite solar cells

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