Dual Organic Spacer Cation Quasi-2D Sn–Pb Perovskite for Solar Cells and Near-Infrared Photodetectors Application

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Tin (Sn)- and Sn–Pb-based perovskites arouse great interests in low-toxicity perovskite. Nevertheless, the instability problems that aroused by Sn oxidation still hinder their applications. To improve the stability of Sn-based perovskite, a relative stable quasi-2D Sn–Pb perovskite is proposed by introducing two mixed organic cations, 2-phenylethylammonium (PEA$^+$), and butylammonium (BA$^+$), which facilitate both precursor assembly and carrier transportation. As a result, efficient and stable quasi-2D Sn–Pb perovskite solar cells (PSCs) with a power conversion efficiency (PCE) of $\approx 10\%$ and an improved open-circuit voltage ($V_{OC}$) of 0.808 V under AM 1.5G illumination are achieved. The maximum power point (MPP) shows that the current of quasi-2D Sn–Pb PSC still maintains 97.7% of original value after 20 000 s. Furthermore, the application of the mixed spacer cation quasi-2D Sn–Pb perovskite in near-infrared (NIR) light detection is demonstrated. Herein, the quasi-2D Sn–Pb perovskite shows a high detectivity of $\approx 6.57 \times 10^{11}$ Jones with n–i–p structure under 850 nm. It is suggested in the results that the quasi-2D Sn–Pb perovskite with improved stability holds great potential in infrared photodetection and imaging application.

1. Introduction

Metal–halide perovskite solar cells (PSCs) have highlighted significant breakthrough in solar power conversion efficiency (PCE) from 3.8%$^{[1]}$ to certified 25.7%$^{[2]}$ in the last 10 years. The application of Pb-based PSCs somehow causes environmental concerns due to their detrimental heavy metals content. Sn-based and mixed Sn–Pb perovskites have been investigated as substitute. With a narrow bandgap from 1.2 to 1.6 eV,$^{[3]}$ the Sn- and Sn–Pb-based PSCs have achieved PCE of 14.81%$^{[4]}$ and 22.02%,$^{[5]}$ respectively. However, Sn-based perovskites still suffer from problems like instability and open-circuit voltage ($V_{OC}$) loss mainly caused by oxidation of Sn$^{2+}$ to Sn$^{4+}$, which induces p-type self-doping in the perovskite.$^{[6]}$ To tackle this issue, passivation layers and reductive additives (e.g., SnF$_2$ and Sn powders$^{[7]}$) were adopted to inhibit Sn oxidation. Low-dimensional structures were also verified as effectively way to promote the stability of quasi-2D Tin perovskite solar cells.$^{[8]}$ The fact that mixed Sn–Pb perovskites extends the photo absorption range to the near-infrared (NIR) region, with absorption wavelengths up to 1050 nm,$^{[9]}$ has rendered them attractive material for NIR photodetection. Similar to its solar cell device counterpart, Pb–Sn-based perovskite photodiodes (PPDs) also suffer from instability and high dark current issues.$^{[10]}$

In 2D or quasi-2D perovskite, the n layers of inorganic material are separated by a hydrophobic long-chain organic cation, and generally show improved stability. Here, we employed both PEA$^+$ ($C_6H_5(CH_2)_2NH_3^+$) and BA$^+$ ($C_4H_9NH_3^+$) organic spacer cations to form quasi-2D Sn–Pb perovskite. It has been reported that unsaturated alkylamine cation (PEA$^+$) can improve carrier transport across the absorber layer while long-chain alkylamine cation (BA$^+$) facilitates precursor assembly and orientated crystal growth.$^{[11]}$ It is also reported that a 3-aminopropyltriethoxysilane (APTES) self-assembled monolayer (SAM) layer could improve the morphology of perovskite films and enhance the interfacial contact.$^{[12]}$ Combining these two strategies, we obtained quasi-2D perovskite films with relatively concentrated phase distribution, and relatively stable quasi-2D Sn–Pb PSCs with a PCE of $\approx 10\%$ and a $V_{OC}$ of 0.808 V. The high-quality quasi-2D Pb–Sn PPDs, in either n–i–p or p–i–n configuration, are then constructed for NIR photodetection. The quasi-2D Pb–Sn PPDs present excellent NIR detection performance with a detectivity of $\approx 10^{11}$ Jones at 850 nm.

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DOI: 10.1002/adpr.202200079

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2. Results and Discussion

The synthesis process for the mix organic cation perovskite is shown in Figure 1a. BA$_2$MA$_3$Pb$_4$I$_{13}$ and PEA$_2$FA$_3$Sn$_4$I$_{13}$ precursor solution were prepared separately, and then blended together according to volume ratio. The high-quality quasi-2D Sn–Pb perovskite films were then prepared by hot-casting method. In experiment, device with n–i–p and p–i–n configuration were fabricated with schematic views shown in Figure 1b. To obtain optimum perovskite thin film for photovoltaic application, solar cell devices from different mixing ratio of BA$_2$MA$_3$Pb$_4$I$_{13}$ and PEA$_2$FA$_3$Sn$_4$I$_{13}$ precursors were fabricated. The short-circuit current density $J_{sc}$ and the open-circuit voltage $V_{oc}$ of these devices are summarized in Figure 1c. It is found that the dark current density $J_{d}$ increases with the ratio of Sn/Pb in the precursor. Among them, the device with Pb/Sn ratio of 6:4 gives an overall best performance when considering both $J_{sc}$ and $V_{oc}$. Figure S1, Supporting Information further shows the external quantum efficiency (EQE) curves of (BA$_2$MA$_3$Pb$_4$I$_{13}$)$_{0.6}$(PEA$_2$FA$_3$Sn$_4$I$_{13}$)$_{0.4}$. Similar to the 3D Sn–Pb perovskite, the mixed organic cation perovskite shows EQE wavelength range extending to the NIR region, reaching 1000 nm. It is found that the EQE of the quasi-2D perovskite PSC in the NIR region increase as the ratio of Sn/Pb increases. The device with Pb/Sn ratio of 6:4, denoted as (BA$_2$MA$_3$Pb$_4$I$_{13}$)$_{0.6}$(PEA$_2$FA$_3$Sn$_4$I$_{13}$)$_{0.4}$, has the highest EQE values in the NIR region.

Therefore, precursor with Pb/Sn ratio of 6:4 is adopted for the following experiments.

As is shown in Figure 2a, the scanning electron microscopy (SEM) image shows the surface morphology of the (BA–PEA)$_2$(MA–FA)$_3$Pb$_{0.6}$Sn$_{0.4}$I$_{13}$ perovskite film prepared with APTES interlayer. The quasi-2D perovskite film shows smooth surface without any pinholes and excellent crystallization, with crystal size larger than 1 μm. There are two dominant X-ray diffraction (XRD) peaks at 14.25° and 28.51° in the XRD spectra in Figure 2b, which correspond to the (111) and (202) diffraction planes, respectively.

There is a weak peak at θ=13.2° which probably corresponds to (010) diffraction plane. The optical absorption spectra of the quasi-2D Pb–Sn perovskite shows an absorption step at ≈640 nm (Figure 2c), followed by a low absorption tail extending to wavelength longer than 950 nm. It indicates that the actual absorption edge may be located at the longer wavelength.

Photoluminescence (PL) measurements were excited from both the front side (perovskite surface) as well as the back side (glass side). As shown in Figure 2c, the emission peak of 960 nm is observed, which is close to the previous reported $n = 4$ PL peak of the quasi-2D Sn-based perovskite. The same PL peak position was found when the excitation light (405 nm) is irradiated from both the front (air side) and back sides (glass), which means there is no difference in phase distribution at the bottom of the perovskite films and the upper surface of the perovskite film. This result suggests the relative consistent phase distribution of the quasi-2D Sn–Pb perovskite film in vertical direction. In addition, we also measured PL spectrum of five different sites on perovskite film surface. As shown in Figure S2, Supporting Materials.
Information, there is also no PL peak shift at the five different locations on the perovskite film. Hence, there is a uniform-phase distribution in the dual organic spacer cation quasi-2D Sn–Pb perovskite film. The PL spectrum results indicate that there is a relative concentrate phase distribution in both lateral and vertical direction of our quasi-2D Sn–Pb perovskite film. The ultrafast transient absorption (TA) spectroscopy is used to investigate the charge-carrier dynamics in quasi-2D Pb–Sn perovskite films. The films were initially pumped from the front side (air side), and Figure 2e shows their ground-state bleaching (GSB) signals. As expected, there is an obvious GSB peak at 943 nm in NIR range, which is consistent with PL results.

In low-dimensional tin-based perovskites, organic spacer cations isolating the [SnI₆]⁴⁻ inorganic octahedral sheets will increase air stability of low-dimensional perovskites. The organic spacer cation layers act as “barriers” to form quantum well structures with quantum confinement effects, restraining self-doping effect within Sn-based perovskites. To reveal the valence state of the Sn content in the quasi-2D (BA₂MA₃Pb₄I₁₃)₀.₆(PEA₂FA₃Sn₄I₁₃)₀.₄ perovskite, X-ray photoelectron spectroscopy (XPS) measurements were performed. The XPS results are shown in Figure 2d. The two peaks deconvoluted from the Sn 3d⁵/₂ peak at 486.4 and 487.1 eV are attributed to Sn²⁺ and Sn⁴⁺ in quasi-2D Sn–Pb perovskite films.
perovskite, respectively. The absence of the 487.1 eV peak in the quasi-2D perovskite film implies that low-dimensional tin perovskite prevents the oxidation of Sn$^{2+}$ in the film. For comparison, a significant Sn$^{4+}$ content is found in a 3D Sn–Pb perovskite film.

2.1. Quasi-2D Pb–Sn PSC

The typical current–voltage characteristic curves of the quasi-2D Pb–Sn PSCs, with device structure of indium tin oxide (ITO)/Poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT: PSS)/APTES/perovskite/[6,6]-Phenyl-C61-butyric acid methyl ester (PCBM)/2,9-Dimethyl-4,7-diphenyl-1,10-phenanthroline (BCP)/Ag, are shown in Figure 3a. It is found that, with APTES layer on PEDOT:PSS, the fill factor (FF) of the PSC is promoted to 71.24%, and the $V_{oc}$ increased to 0.82 V, resulting in an overall PCE of $\approx 10\%$. This is 40% enhancement of PCE compared to device without APTES. The detailed results are listed in Table S1, Supporting Information. This result indicates that APTES layer not only enhance the affinity of PEDOT:PSS, but also improve the perovskite films crystallinity and passivate the trap states at the perovskite surface due to hydrogen bonding via its terminal groups.\cite{16} It is worth mentioning that the optical bandgap ($E_g$) of perovskite materials can be manipulated by engineering their compositions.\cite{9, 17, 18} The effective absorption edge actually extends to NIR wavelengths, though the absorption coefficient is low in Figure 2c. The EQE spectrum of quasi-2D Pb–Sn perovskite verifies this point. As displayed in Figure 3b, the EQE wavelength range extends from 300 to 1000 nm. The integrated $J_{sc}$ obtained from EQE curve of APTES-modified quasi-2D PSC is 16.11 mA cm$^{-2}$ while the control one is 14.75 mA cm$^{-2}$, which both keep deviation from the measured $J_{sc}$ value less than 10%.

Previous studies have shown that 2D structure not only enhances thermodynamic stability by suppressing the vacancy defects and the oxidation of Sn$^{2+}$ ions\cite{14, 19} but also enhances the moisture stability due to the long hydrophobic alkyl chains of the organic spacer.\cite{20} The mixed organic spacer quasi-2D photovoltaic device has higher stability under continuous illumination, when compared to 3D Pb–Sn perovskite PSC. The $J_{sc}$ only declined slightly after 18h continuous AM1.5 illumination, as shown in Figure S3, Supporting Information. Moreover, even the maximum power point (MPP) tracking curve in Figure 3c shows that the current still maintains 97.7% of original value after 20000 s continuous AM1.5G illumination. For comparison, Figure 3d shows the stability test results of quasi-2D Sn–Pb PSC and 3D (FASnI$_3$)$_{0.4}$(MAPbI$_3$)$_{0.6}$ PSC with the same structure. Storing in nitrogen glove box environment, the PCE still maintained 96% of its original value for the quasi-2D Sn–Pb PSC after 30 days whereas PCE of 3D Sn–Pb PSC dropped to 44% of its original value just at 8th day. Meanwhile, the $V_{oc}$ of 3D Sn–Pb PSC kept going down, whereas the $V_{oc}$ of quasi-2D one increased slightly and reached at 0.827 V after 30 days.

Figure 3. a) Current density–voltage ($J$–$V$) curves of devices with and without 3-aminopropyltriethoxysilane (APTES). b) EQE and integrated $J_{sc}$ of PSCs with APTES modified and without (w/o) APTES layer. c) Maximum power point (MPP) tracking curve of the PSC with APTES interlayer for a duration of 20000 s. d) Long-term stability of quasi-2D Pb–Sn PSCs and 3D (MAPbI$_3$)$_{0.6}$(FASnI$_3$)$_{0.4}$ PSC. All devices are unencapsulated and stored in glove box, and the humidity and temperature in glove box maintain at 10% and 24 °C, respectively.
The specific photocurrent–voltage (I–V) curves of 3D Sn–Pb PSC are shown in Figure S4, Supporting Information and detailed data is presented in Table S2, Supporting Information. It is obvious that the mixed organic cation quasi-2D Sn–Pb PSCs get considerable improvement in terms of device stability.

2.2. Quasi-2D Sn–Pb Perovskite Photodetector

This absorption range and stability results of quasi 2D Pb-Sn perovskite spark our interest in optoelectronic property of NIR photodetectors. We have measured the photo response to 850 nm light of the photodiode (PD1) with a p-i-n planar structure of ITO/PEDOT:PSS/Perovskite/PCBM/BCP/Ag. Unlike solar cell application, photodetectors are prepared without APTES inter layer. The cross-sectional SEM image of PD1 is presented in Figure 4a. The quasi 2D Pb-Sn perovskite film is ≈105 nm. The corresponding I–V characteristics under 850 nm incident light with different light intensity are presented in Figure 4b. Similar to solar cell, there is an $V_{oc}$ at the device terminal under illumination, which indicates that the PD1 can be operated in self-powered condition. The photocurrent increases with the incident light intensity. The linear relationship between photocurrent density and incident light intensity at −0.1 V is plotted in Figure 4c. Under 850 nm light, the photocurrent density reaches 0.01 A cm$^{-2}$ at a light intensity of ≈175 mW cm$^{-2}$ (light spot size is $2.16 \times 10^{-4}$ cm$^2$). Meanwhile, the $J_d$ is $4 \times 10^{-8}$ A cm$^{-2}$ (device size is 0.038 cm$^2$). The photocurrent at 55.33 μW cm$^{-2}$ is $1.76 \times 10^{-7}$ A cm$^{-2}$. A linear dynamic range (LDR) of 95 dB at 850 nm light is calculated.

The device responsivity then is calculated as $R = (I_p - I_d)/P_{in}A$. $I_p$ is photocurrent, $I_d$ is dark current, $P_{in}$ is the incident light intensity, and $A$ is light spot area because device area is

![Figure 4](image-url)

**Figure 4.** a) Cross-sectional SEM image of photodiode (PD1, scale bar: 200 nm). b) Photocurrent–voltage (I–V) curves of PD1 under 850 nm with different intensity. c) Photocurrent density of PD1 versus incident light intensity at −0.1 V. d) Transient photocurrent of the PD1 without any encapsulation under 550 nm pulse light with 800 Hz at 0 V bias in the ambient environment. e) Dark currents and photocurrents under AM1.5 illumination of PD1 and PD2. f) The noise currents of PD1 and PD2 under 0 V and −0.1 V bias.
bigger than light spot. The device-specific detectivity is evaluated by \( D^* = (Af)^{1/2}/(i_{n}/R) \), where \( A \) is the effective area of the detector, \( f \) is the bandwidth, and \( i_{n} \) is the noise current. When the dark current is dominated by the shot noise, \( D^* \) can be expressed as \( D^* = R/(2qi_{n})^{1/2} \), where \( q \) is the elementary charge. A responsivity of 0.16 A W\(^{-1}\) and a \( D^* \) of 1.42 \( \times 10^{12} \) is obtained under 850 nm of 4.65 mW cm\(^{-2}\). This detectivity value may be overestimated due to the shot noise assumption. To precisely evaluate the \( D^* \) of the PDs, other noise contributions have to be considered, such as 1/f noise in the low-frequency range and thermal noise generated by thermal excitation of charge carriers. We then measured the noise power spectra of the PD1. As shown in Figure 4f, a noise current of 19.24 pA Hz\(^{-1/2}\) at a modulation frequency of 100 Hz at −0.1 V is obtained. The recalculated \( D^* \) using noise current is 3.05 \( \times 10^{10} \) Jones. When operated in self-power mode (biased at 0 V), an \( R \) of 0.15 A W\(^{-1}\) at 850 nm can be calculated from the EQE results, as shown in Figure S5a,b, Supporting Information. According to Figure 4f, the noise current is 0.657 pA Hz\(^{-1/2}\) at a modulation frequency of 100 Hz at 0 V, then the calculated \( D^* \) is 4.39 \( \times 10^{11} \) Jones. The difference in the specific detectivity of PD1 under different bias was mainly caused by the different noise currents.

The response speed is another important parameter for photodetectors. The measurement of our quasi-2D Pb–Sn perovskite photodetectors (PPDs) was performed under a 550 nm pulse light. Figure 4d shows the transient photocurrents of the devices measured under 0 bias and a pulse frequency of 800 Hz. The resulting photocurrent shows clear “on” and “off” states. The transient response result shows a rise time \( (t_{r}) \) (output signal changing from 10% to 90% of the peak output value) of 148 \( \mu \)s and a decay time \( (t_{d}) \) (output signal changing from 90% to 10% of the peak output value) of 125 \( \mu \)s.

To compare the performance of photodetector configurations, a n–i–p photodiode with poly[3-hexylthiophene-2,5-diyl] (P3HT) hole transport layer was also fabricated. The device structure is ITO/SnO\(_{2}/\)Perovskite/P3HT/Au, denoted as PD2. P3HT is chosen here because of its capability for mass production in low cost, and its low-energy barrier for hole extraction is compared to other conducting polymers (i.e., Poly[bis(4-phenyl)(2,6,6-trimethylphenyl)amine (PTAA), Poly[N,N'-bis-4-butylnylidene-N,N'-bisphenyl]benzidine (poly-TPD), and Poly[2.2'-5'].2''-5''-quaterthiophene] -5.5''-diyl] (PDCBT)). PD2 has an NIR-responsive range and responsivity that are similar to PD1, as shown in Figure S6a,b, Supporting Information. Photocurrents increase linearly with incident intensity and the best R of 0.177 A W\(^{-1}\) is obtained at relative weak light intensity of 0.202 mW cm\(^{-2}\). The response speed is also characterized. Showing in Figure S6c, Supporting Information, the rise time and decay time reach 117 and 119 \( \mu \)s, respectively, under the same testing condition as PD1. Moreover, the transient response of both PD1 and PD2 under different light pulse frequency was also characterized (as shown in Figure S7, Supporting Information), which verifies that the respond speed of PD2 is slightly faster than that of PD1. As shown in Figure 4e, dark current of PD2 under large reversed biased is flatter and lower compared to that of the PD1. This can also be verified in noise current power spectral. As shown in Figure 4f, the total noise currents of both PD1 and PD2 are dominated by 1/f noise in the low-frequency range and almost the same under zero bias. However, noise current of PD1 increases from 10\(^{25}\) to 10\(^{23}\) A\(^{2}\) Hz\(^{-1}\) in the high frequency under high reverse voltage bias, whereas there is nearly no difference in the noise current of PD2 under the same bias condition. According to the noise spectrum in Figure 4f, PD2 exhibits a noise current of 0.525 pA Hz\(^{-1/2}\) at 100 Hz at −0.1 V. The calculated specific detectivity \( D^* \) is 6.57 \( \times 10^{11} \) Jones. Therefore, the n–i–p PD2, with a lower noise, higher detectivity, and faster response speed, is considered as a better device configuration for photodetection applications.

3. Conclusions

We have developed a quasi-2D Sn–Pb perovskite with dual organic spacer cations, and explored applications as solar cells and NIR photodetectors. The quasi-2D Sn–Pb PSC shows good stability under continuous illumination and good storage life time, with a \( V_{oc} \) and a PCE of 0.808 V and 10%. When applied as photodetectors, the quasi-2D PPDs with n–i–p structure shows a lower reverse dark current compared to its p–i–n counterpart, resulting in a high detectivity of 6.57 \( \times 10^{11} \) Jones at 850 nm when operated at −0.1 V. The mixed organic spacers cations approach is a promising method for getting high-stability quasi-2D Sn–Pb perovskite optoelectronic devices.

4. Experimental Section

Quasi 2D Sn–Pb Perovskite: All materials were purchased without any further processing. The quasi-2D perovskite precursor solutions (PEA)\(_2\)(FA)\(_2\)Sn\(_2\)I\(_4\) and (BA)\(_2\)(MA)\(_2\)Pb\(_2\)I\(_6\) were prepared by dissolving 2-Phenylethylamine Hydroiodide (PEA):formamidinium iodide (FAI):SnI\(_2\) and n-Butylammonium iodide (BAI):methylammonium iodide (MAI):PbI\(_2\) with a molar ratio of 2:3:4 in the mix solvent dimethylformamide: dimethyl sulfoxide (N,N -dimethylformamide (DMF):dimethyl sulfoxide (DMSO)): 4:1 volume ratio) at 0.3 M concentration. SnF\(_2\) was added to (PEA)\(_2\)(FA)\(_2\)Sn\(_2\)I\(_4\) as 10% molar ratio of Sn. And then, quasi-2D Sn–Pb perovskite precursor solution was obtained by mixing (PEA)\(_2\)(FA)\(_2\)Sn\(_2\)I\(_4\) and (BA)\(_2\)(MA)\(_2\)Pb\(_2\)I\(_6\) at volume ratio of 4:6. Finally, the solution was filtered with a 0.22 \( \mu \)m polytetrafluoroethylene (PTFE) filter prior to use.

Device Fabrication: All of PEDOT:PSS, PCBM, and BCP layers in PSCs with structure of ITO/PEDOT:PSS/APTES/perovskite/PCBM/BCP/Au were spin-coated. ITO glass was first cleaned by deionized water followed by ultrasonication with acetone and ethanol for 10 min respectively. Then, the substrates were dried by nitrogen flow and treated with ultraviolet/ozone for 10 min. PEDOT:PSS layer was spin-coated at 3000 rpm for 30 s and annealed at 150°C for 20 min. The 50 \( \mu \)L APTES/chlorobenzene (CB) (1:10, v/v) was spun-coated dynamically at 3000 rpm for 30 s on PEDOT layer. As for perovskite, both substrates and quasi-2D Sn–Pb perovskite precursor solution were preheated for 10 min at 90 °C, and then perovskite precursor was spin-coated at 4000 rpm for 40 s and annealed at 100 °C for 10 min. Next, PCBM of 20 mg mL\(^{-1}\) in CB was fabricated at 2000 rpm for 60 s and annealed at 100 °C for 10 min. Finally, 80 nm of Ag electrode was thermally evaporated on the film.

For PD2, SnO\(_2\) solution was spin-coated onto the cleaned ITO glass at 3000 rpm for 30 s and annealed at 180 °C for 30 min in air. Before transferring substrates to the glove box, substrates were treated with ultraviolet/ozone for 10 min. P3HT solution (20 mg mL\(^{-1}\) in CB) was then spin-coated onto the perovskite film at 2000 rpm for 60 s and annealed at 100 °C for 10 min. And, Au electrode of 80 nm was evaporated finally. The other process was the same as PD1.

3D (FA\(_{0.13}\)MA\(_{0.87}\))\(_2\)(MAPb\(_{3}\)I\(_{13}\)) 0.6 Solar Cell: MAPb\(_3\)I\(_{13}\) precursor solution was prepared by dissolving methylamine hydroiodide (161 mg) and PbI\(_2\) (462 mg) in a mixed solvent of DFM (640 \( \mu \)L) and DMSO (160 \( \mu \)L) while
formamidine hydroiodide (172 mg), SnI₂ (372 mg), and SnF₂ (15.6 mg) were dissolved in a mixed solvent of DMF (500 μL) and DMSO (100 μL) to constitute the precursor solution of FASnI₃. Then, the binary metal perovskite precursor solution was prepared by mixing MAPbI₃ (500 μL) and FASnI₃ (400 μL) precursor solutions. The 45 μL perovskite precursor was dipped onto the SnO₂ layer and spin-coated at 4000 rpm in the glove box. The antisolvent anisole was dipped in situ onto the substrate at the seventh second. The other process was the same as PD1.

Device Characterization: The photodiodes were electrically characterized by Keithley 2400 source meter under light and dark conditions at room temperature. The photovoltaic response of photodetectors was characterized in the air by MATATEST E2 photoelectric testing system in the dark or under illumination with an LED (λ = 850 nm). And the EQE was measured by SolarCellScan100. The absorbance spectra were obtained using Shimadzu UV-2600 UV–vis spectrophotometer. SEM images were scanned by ZEISS SUPRA 55. Transient absorption spectroscopy data was obtained by Newport Transient Absorption Spectroscopy. PL spectrum was measured via PL spectrometer (LTF-3000, QSpec, Biaoqi, Guangzhou) with a 405 nm laser as the excitation source. XPS was characterized by in situ XPS (PHI5000 Versa Probe II).

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

Acknowledgements
This work is financially supported by the National Natural Science Foundation of China (Grant nos. 61974006 and 61774174), and the Shenzhen Municipal Scientific Program (Grant nos. JCYJ2020109140610435 and SGDX2020110395607022). The authors would like to acknowledge Prof. Tingchao He and Miss. Junzi Li from Shenzhen University for ultrafast transient absorption spectra measurement.

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
NIR photodetectors, quasi-2D Sn–Pb perovskites, solar cells, stability

Received: March 21, 2022
Revised: May 1, 2022
Published online: May 29, 2022

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