

Effect of Alkali-Metal Additive on Rudorffite AgBiI₄-Based Pb-Free Solar Cells

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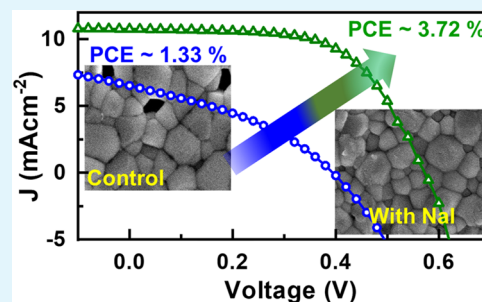
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ABSTRACT: Rudorffite material, silver bismuth iodide, is one of the promising lead-free alternatives for photovoltaic applications due to its high absorption coefficient, low toxicity, and relatively better stability. Here, we report on the effects of alkali halide additive in the absorber material AgBiI₄, focusing on its material properties and solar cell devices. The inclusion of NaI significantly improved the film quality with compact and pinhole-free morphology and better crystallinity. The device with rudorffite material with NaI additive demonstrated a notable increase in the PCE from 1.33 to 3.72%, along with improved device stability. The device analysis confirmed that NaI incorporation in AgBiI₄ modulates the optoelectronic quality, effectively suppressing charge recombination and enhancing charge extraction within the device. Thus, this work corroborates that additive engineering is an effective strategy for improving both the efficiency and stability of AgBiI₄-based rudorffite solar cells, underscoring their potential in sustainable photovoltaic applications.

KEYWORDS: lead-free, Ag–Bi–I system, rudorffite, additive, photovoltaic, defect passivation



1. INTRODUCTION

Halide perovskites have demonstrated a startling power conversion efficiency (PCE) of over 26% for single-junction devices.^{1,2} Despite having such remarkable properties, the presence of toxic lead and instability toward moisture, air, and temperature is a major limitation.^{3–6} Exploring less toxic and stable absorber materials is crucial for developing effective lead-free alternatives. Sn and Ge, being members of the same group as Pb, are the first choices to substitute for Pb. Despite the lower toxicity of Ge and Sn, perovskites with Sn and Ge are relatively less stable in ambient conditions due to the easy oxidation of Sn²⁺ and Ge²⁺ to Sn⁴⁺ and Ge⁴⁺, respectively, and hence add challenges for photovoltaic applications.^{7,8} It is known that Bi³⁺ is relatively less toxic compared to Sn²⁺.⁹ Furthermore, Bi³⁺ also shares a similar electronic configuration with Pb²⁺, i.e., (6s²6p⁰), making it an attractive alternative for developing bismuth-halide-based solar cells such as CH₃NH₃BiI₄, A₃BiI₉ (A = Cs, Rb, K),^{10,11} Cs₂AgBiX₆,^{12–14} etc. However, due to the indirect nature and wide bandgap of these materials, they are not feasible for single-junction solar cells.

Recently, ternary Ag–Bi–I materials have been explored as potential candidates for solar cell application as the light-absorbing material due to their lower toxicity and relatively high stability against air and moisture.^{15,16} These silver bismuth iodides are known as rudorffites, having the general formula C'C''X₂, where both C' and C'' are sites in the cation sublattice with coordination no. 6, and X is a monovalent anion. C' and C'' form octahedra with the X, arranged

alternately in the rudorffite structure. These octahedra do not share corners, unlike 3D halide perovskites.¹⁶ It has been reported that thermodynamically stable rudorffite materials such as Ag₃BiI₆, Ag₂BiI₅, AgBiI₄, and AgBi₂I₇, have potential in solar cell applications.¹⁶ The direct bandgap of the silver iodo-bismuthates is approximately 1.8 eV, which is a suitable value for tandem solar cells.¹⁷ Sargent et al. reported a PCE of 1.22% with AgBi₂I₇ solar cell device having a bandgap of 1.87 eV.¹⁸ Turkevych et al. have documented a detailed growth study of silver bismuth iodide as the absorbing material and reported a decent PCE of 4.3% with mesoporous and compact TiO₂ n-i-p configuration.¹⁶ Some reports documented compositional engineering with modulation of the electronic and photo-optical properties of Ag–Bi–I-based solar cells.^{19,20} To control the kinetics of film formation, regulating the dissolving process is important, like dissolving the precursors in one solvent or a mixture of solvents and various antisolvents that lead to different morphologies.^{21,22} Golobostanfar and co-workers reported solvent engineering for controlled crystal growth of rudorffite absorbers by varying the mixture composition of dimethylformamide (DMF) and dimethyl sulfoxide (DMSO). Additionally, additive engineering is crucial for enhancing the

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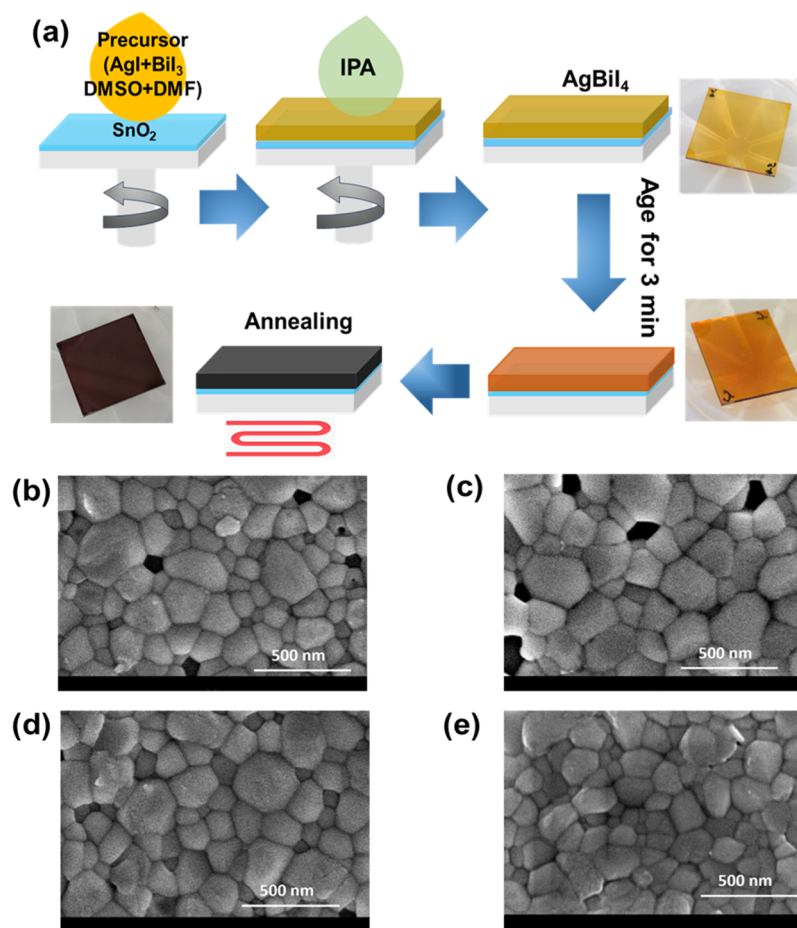


Figure 1. (a) Schematic of a one-step spin coating for the preparation of AgBiI_4 films. Comparative SEM images of AgBiI_4 film with different concentrations of NaI additive: (b) 0, (c) ~ 0.5 , (d) ~ 1 , and (e) ~ 2 mol % NaI, respectively.

film quality by promoting crystallization and passivating defects. Multiple reports demonstrated that additive engineering, such as inorganic halide derivatives and functional molecular additives, benefits hybrid perovskites^{23–26} and rudorffites-based devices.^{27,28} Wang et al. reported AgBiI_4 absorber layer incorporating Cs^+ resulting in improved film quality and a PCE of 1.58%.²⁷ Functional additives such as Lewis base thiourea,²⁸ lithium bis(trifluoromethylsulfonyl)imide,²⁹ etc. have also been reported to be beneficial for the improvement in AgBiI_4 solar cells. Despite multiple approaches, the efficiency of the Ag–Bi–I-based solar cell is quite low compared with the ideal value. This underscores the need for further advancements in material and transport engineering to achieve competitive performance in rudorffite-based solar cells.

In this work, we have investigated the effect of alkali halide additive on AgBiI_4 , a bandgap of approximately 1.84 eV, as a Pb-free light-absorbing material. We examined the effect of Na^+ ions on the morphology of the film and the material chemistry. It was found that the film quality was significantly improved with well-covered film and compact surface morphology and ameliorated the surface chemistry for the AgBiI_4 film with NaI additive. To evaluate the influence of additives, we fabricated solar cells with $\text{ITO}/\text{SnO}_2/\text{AgBiI}_4\text{--NaI}/\text{poly}[\text{bis}(4\text{-phenyl})(2,4,6\text{-trimethylphenyl})\text{amine}]$ (PTAA)/Ag as the n-i-p configuration. With the introduction of the Na^+ additive, the PCE of the device was achieved as high as 3.72% with a significant increase in the device parameters.

This report has discussed an in-depth study of AgBiI_4 , the thin film growth, and the photophysics of the device.

2. EXPERIMENTAL SECTION

2.1. Chemicals Used. AgI (99.999%), BiI_3 (99%), sodium iodide (NaI, 99.9%), dimethyl sulfoxide (DMSO), N,N-dimethylformamide (DMF), and poly[bis(4-phenyl)(2,4,6-trimethylphenyl)amine] (PTAA) purchased from Sigma-Aldrich, and SnO_2 colloid (tin(IV) oxide) purchased from Alfa Aesar were used without any further purification. The FTO-coated and ITO-coated glasses purchased from Yingkou OPV Tech Co., Ltd. were used throughout the deposition process.

2.2. Preparation of NaI:AgBiI₄ Thin Film and Device.

2.2.1. Preparation of Precursor Solution. A 0.6 M AgBiI_4 precursor solution was prepared by dissolving a 1:1 molar ratio of BiI_3 and AgI (v/v) in a 4:1 mixture of DMSO and DMF, followed by stirring at room temperature for 12 h. For the NaI additive-based solution, different amounts of NaI (0.5, 1, 2, and 4 mg/mL) were added, which corresponds to 0.55, 1.11, 2.20%, and 4.46 mol % of NaI, respectively. These are written as 0, 0.5, 1, 2, and 4 mol % in the text for the sake of ease. The solutions were filtered by using a 0.22 μm pore-sized filter.

2.2.2. Spin Coating ETL. Following a thorough cleaning, glass substrates coated with indium tin oxide (ITO) were exposed to UV ozone for 15 min. The SnO_2 colloid precursor (Alfa Aesar, 15% in H_2O colloidal dispersion) was diluted to 3% in distilled water. On the ITO substrates, a compact layer of SnO_2 was spin-coated for 30 s at 3000 rpm. This SnO_2 layer was annealed at 150 $^\circ\text{C}$ for 30 min in ambient air and cooled to room temperature.

2.2.3. Spin Coating Absorber Layer. The SnO_2 -coated glasses were treated with UV ozone for 30 min before the spin coating of the

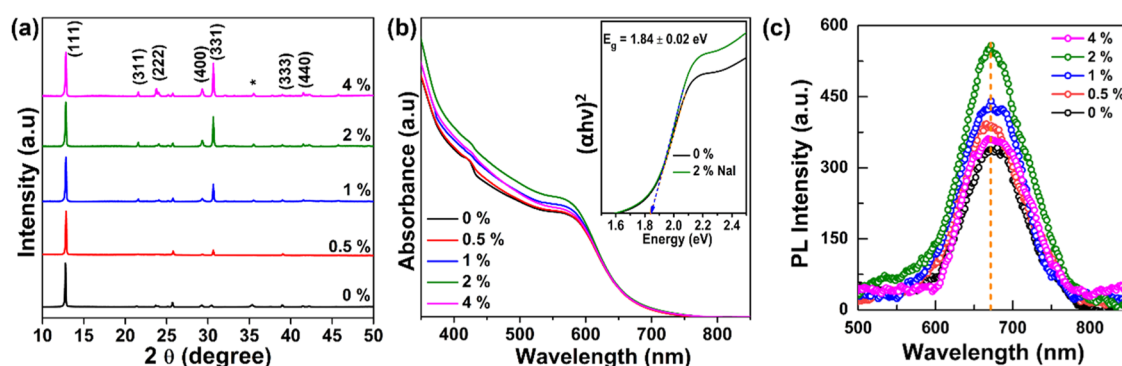


Figure 2. (a) XRD patterns (* is the ITO peak), (b) UV-vis spectral, and (c) PL spectra of AgBiI₄ films with NaI additive (0, 0.5, 1, 2, and 4 mol %).

absorber (AgBiI₄ and NaI:AgBiI₄) layer. NaI additives (0.5, 1, 2, and 4) mol % in AgBiI₄ precursors were spin-coated at 1000 rpm for 10 s (ramping slope 2 s) and 4000 rpm for 40 s followed by dripping 700 μ L of isopropyl alcohol (IPA) at 33rd second of the second step and then the coated glasses were aged for 3 min before annealing at 100 $^{\circ}$ C for 15 min and 130 $^{\circ}$ C for 15 min.

2.2.4. Solar Cell Fabrication. The photovoltaic devices were fabricated on precleaned patterned ITO-coated glass substrates. The ITO substrates were properly cleaned to remove organic residues, dust, and any unwanted impurities. First, the substrates were immersed in an ultrasonic bath with pure water, detergent, and 2-propanol, then treated with UV ozone for 5 min. After this, all of the steps mentioned above were followed. PTAA was spin-coated after cooling the absorber layer-coated substrate to room temperature at 3000 rpm for 30 s (ramping slope 2) and then placed on the hot plate at 70 $^{\circ}$ C for 10 min. To complete the device structure, $\sim$ 160 nm of Ag was thermally evaporated (at a pressure $<10^{-4}$ Pa).

2.3. Characterizations. The XRD patterns of all of the NaI:AgBiI₄ films were taken by using Rigaku SmartLab (CuK α radiation, 1.54 $\text{\AA}$) at room temperature. The film morphology and various cross-sectional images were taken by a high-resolution scanning electron microscope (SEM) at a 5 kV accelerating voltage (by Hitachi, S-4800). XPS spectra were obtained using a Versa Probe II instrument (ULVAC-PHI, Japan). The thin films for XPS analysis were prepared inside an N₂-filled glovebox and transferred to the XPS chamber using an N₂-filled transfer vessel to prevent oxygen contamination. The XPS measurements were conducted by using a nonmonochromatic Al K α source (1486.6 eV) with a spot size ranging from 10 to 300 μ m. A pass energy of 187.85 eV (1.5 eV step size) was used for the survey scan, while a pass energy of 46.95 eV (0.1 eV step size) was applied for the fine scan with a spot size of 100 μ m. The spectra were calibrated using the binding energy of 284.8 eV for the C 1s peak.

The absorption spectra of various films were measured by using a UV-vis-NIR spectrometer (UV-2600i, Shimadzu). Emission spectra were collected by a micro-PL spectrometer (HORIBA, LabRamHR-PL NF(UV-NIR)) equipped with a $\sim$ 532 nm laser diode (10 mW cm^{-2}) as an excitation source ($\lambda=420$ nm) was used for obtaining the photoluminescence (PL) spectra. The carrier lifetimes were measured with a fluorescence lifetime spectrometer (Quantaaurus- τ from Hamamatsu-Photonics K.K., C11367) equipped with a $\sim$ 405 nm laser diode (typical peak power of 400 mW) at a 200 kHz repetition rate.

The J - V curves were measured at the scan rate of 0.05 V s^{-1} under one sun with an AM1.5G spectral filter (100 mW cm^{-2}) coupled with an MPPT system (System house Sunrise Corp.). The light intensity was calibrated by a silicon (Si) diode (BS-520BK). The external quantum efficiency (EQE) spectra were recorded by using a spectrometer (SM-250 IQE, Bunkoeki, Japan). The transient photovoltage was measured by using a commercial PAIOS system (PAIOS V.4.3), with a pulse intensity applied to generate a photovoltage spike.

3. RESULTS AND DISCUSSION

3.1. Effect of Alkali Halide Additive on Rudorffite Film Growth and Material Properties.

A schematic illustration for the preparation of AgBiI₄ films is depicted in Figure 1a. The crystalline growth mechanism plays a crucial role in determining the film quality of AgBiI₄. We investigated the effect of the NaI additive on the surface morphology of the AgBiI₄ film by using scanning electron microscopy (SEM) images as given in Figure 1b–e, respectively. The control AgBiI₄ film (Figure 1b) shows multiple pinholes, indicating a less compact microstructure. However, with the addition of NaI, the modified film displays a compact film with significantly fewer pinholes (to a pinhole-free morphology). This improvement suggests that NaI influences the crystallization process of the absorber layer, leading to a more cohesive microstructure.^{30,31} The pinhole-free structure observed in the NaI-modified film is likely to enhance its photovoltaic performance, as a more compact surface could improve charge transport and reduce recombination losses. However, with an excessive amount of NaI, the film was more compact, and some whitish patches were observed, which could be due to the excess NaI on the film's surface. Moreover, compositional analysis (Table S1) using energy-dispersive X-ray spectroscopy (EDS) confirms that the stoichiometry of the precursors is the same as the precursor composition used, further suggesting that the absorber layer has a uniform composition. Interestingly, a slightly iodine-rich composition in the AgBiI₄ film with additive was observed, which could be due to additional iodine from the NaI additive. Elemental mapping (Figure S1) shows a uniform distribution of NaI across the film surface.

To examine the effect of additives on the crystallinity of AgBiI₄ thin films, we measured X-ray diffraction (XRD) patterns. Figure 2a shows the XRD patterns for NaI-additive-based AgBiI₄ films with different NaI concentrations (0, 0.5, 1, 2, and 4 mol %). The dominant peak appears around $2\theta = 12.8^{\circ}$, corresponding to the (111) lattice plane, and other peaks appear at 21.57° , 23.8° , 29.31° , 30.65° , 38.98° , and 41.54° , which correspond to the (311), (222), (400), (331), (333), and (440) planes, respectively. These diffraction patterns are consistent with the cubic defect spinel structure.^{27,32} XRD patterns of NaI-additive-based films closely match with the control film, indicating crystal structure, and the phase remains intact. The dominant XRD peak (111) shows the highest intensity at 2 mol % of NaI, with a minimal shift (Figure S2a and Table S2). The diffraction peak of the (331) plane grows with an increased NaI concentration in the AgBiI₄ film.

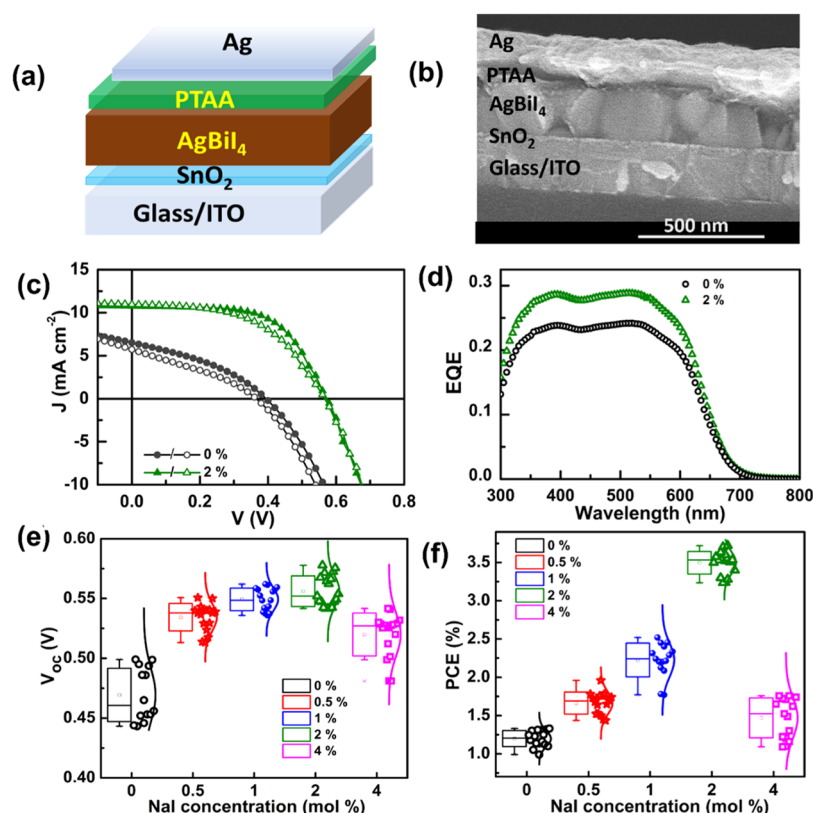


Figure 3. (a) Schematic and (b) cross-sectional SEM image of solar cell device with structure ITO/SnO₂/AgBiI₄/PTAA/Ag. (c) *J*–*V* curve and (d) EQE spectra of the control and NaI-based solar cell device. Statistics of (e) *V*_{oc} and (f) PCE with varying NaI concentration. The error bars on each box indicate the minimum and maximum values, while the middle line represents the median. Small squares within the box denote the mean values.

Table 1. Summary of Device Parameters Obtained from the *J*–*V* Curve Analysis for Control Devices and Devices with the NaI Additive

device	<i>J</i> _{sc} (mA cm ⁻²)	<i>V</i> _{oc} (V)	FF (%)	PCE (%)	Average PCE (%) ± SD
Control (0 mol %)	7.33/6.94	0.49/0.46	37.07/30.84	1.33/0.9	1.19 ± 0.104
NaI- additive (2 mol %)	10.75/10.97	0.58/0.56	60.5/53.2	3.72/3.25	3.49 ± 0.147

Importantly, the enhanced intensity of the dominant XRD peak and the decrease in the full width at half-maxima (fwhm) (as summarized in Table S2 and shown in Figure S2b–f) with increasing NaI concentration implicates the improvement in crystallinity of AgBiI₄ film with NaI additive.

To study the effect of the NaI additive on the optical properties, UV–vis absorption spectra (Figure 2b) were collected. AgBiI₄ exhibits notable absorption in the 360–750 nm range, making it a promising candidate for the absorber layer in solar cell applications. However, its overall absorption properties, like intensity and spectral range, are still inferior to those of Pb-based materials, which could potentially result in lower solar cell performance. AgBiI₄ films with varying NaI amounts show a slight increase in absorbance, while the absorbance onset at 580 nm remains unchanged. By using the Tauc analysis (inset in Figure 2b), the optical bandgap of both control and NaI additive-based AgBiI₄ films was estimated to be almost equal to 1.84 ± 0.02 eV, which is in agreement with the reported literature.^{16,28}

Moreover, we also collected steady-state PL spectra of the NaI additive-based AgBiI₄ films depicted in Figure 2c, and a comparative PL graph is shown in Figure S3. The observed slight increase in PL intensity indicates the improvement in the

optoelectronic quality of AgBiI₄ films with the NaI additive, which is consistent with the observed XRD patterns. The PL intensity enhancement in NaI-based films suggests defect passivation and decrement in nonradiative recombination.^{33,34} It is seen that the PL spectra of the control and additive-based AgBiI₄ films are at almost the same peak position, centered around 672 nm (~1.84 ± 0.02 eV), as estimated from absorption spectra, indicating that the band edge of the AgBiI₄ is unaffected.

3.2. Photovoltaic Characteristic of NaI Additive AgBiI₄ Solar Cells. To investigate the effects of NaI additive on the performance of AgBiI₄ rudorffite solar cells, we then fabricated devices with the ITO/SnO₂/AgBiI₄/PTAA/Ag configuration as shown in the schematic in Figure 3a and the device cross-section SEM image in Figure 3b. Figure 3c shows the *J*–*V* curves for the best control and NaI additive-based devices, and figures of merit are given in Table 1. The *J*–*V* curve of the NaI additive-based device (Figure 3c) demonstrates reduced *J*–*V* hysteresis. The *J*–*V* curves of devices with different NaI concentrations (Figure S4) and the corresponding device parameters (Table S3) are given in the Supporting Information (SI). The device with NaI additive (2%) (hereafter, NaI additive device) demonstrated an optimal

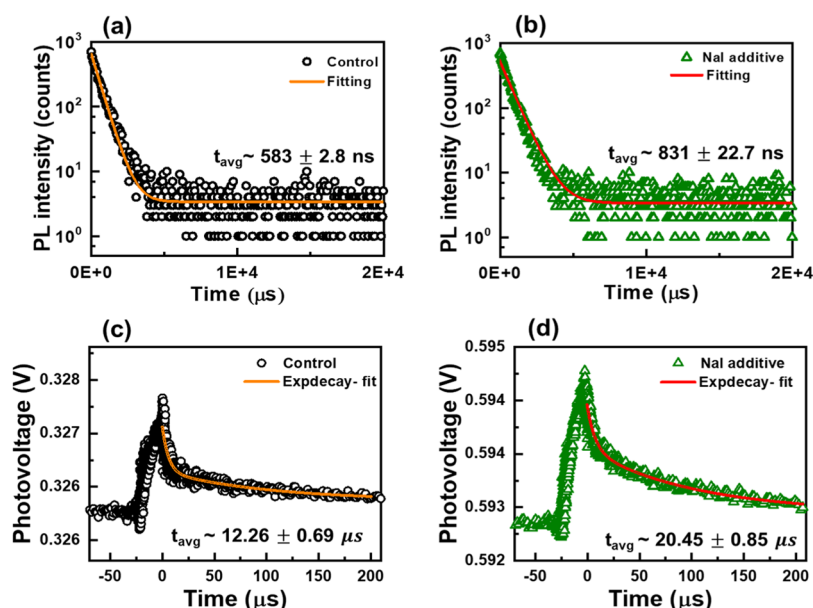


Figure 4. TRPL decay spectra of AgBiI₄ film (a) control and (b) with NaI additive. TPV curves of AgBiI₄-based devices (c) control and (d) with NaI.

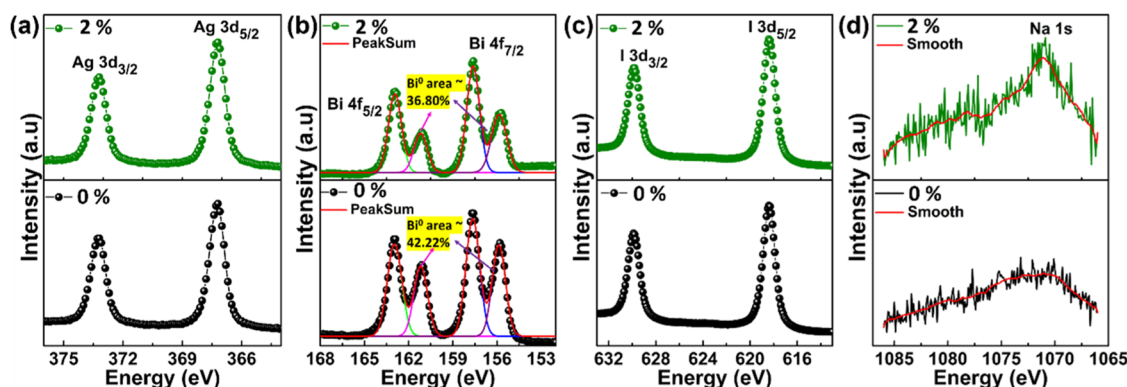


Figure 5. High-resolution XPS spectra of (a) Ag-3d, (b) Bi 4f, (c) I-3d, and (d) Na-1s core energy levels for AgBiI₄ (control) and NaI additive AgBiI₄ films.

PCE of 3.72% compared to the control device with a PCE of 1.33%. Our result is among the best of the reported device performance of rudorffite-based solar cells, as listed in Table S4 and the plot shown in Figure S5. This improvement was accompanied by a notable increase in all device parameters (V_{OC} $\sim$ 0.49 to 0.58 V, J_{SC} $\sim$ 7.33 to 10.74 mA cm⁻², and FF $\sim$ 37.07 to 60.49%), suggesting the passivation of traps and facilitation of effective carrier transport.³⁵

To understand the spectral response, we measured the external quantum efficiency (EQE) of the control and NaI additive devices (Figure 3d). The AgBiI₄ device with NaI additive demonstrated overall enhancement in spectral response, suggesting improvement in both the bulk and interface quality with NaI additive as documented by Fujiwara et al.^{36,37} The EQE spectral analysis (Figure S6) yielded a bandgap of 1.84 ± 0.02 eV, which agrees with the bandgap estimated from the PL spectra and the absorption spectra.

To assess the relationship between alkali-metal ion doping and photovoltaic performance, we conducted the statistical analysis of device parameters (V_{OC} , FF, J_{SC} , and PCE) of 15 devices with different NaI concentrations as depicted in Figure 3e,f and SI (Figure S7, Table S4). These statistical results

display the trend of the device parameters with different NaI additive concentrations. The standard deviation of device parameters has a lower value for the device with NaI additive, indicating higher reproducibility of device results compared to control devices. These results corroborate that the NaI additive in the AgBiI₄ device is beneficial for improvement in device performance and its reproducibility.

3.3. Effect of Additive on Transient Photo Characteristics and Defect Passivation. To study the recombination dynamics and charge transport, we conducted time-resolved photoluminescence (TRPL) measurements. The TRPL spectra for AgBiI₄ films on ITO (Figure 4a,b) and ITO/SnO₂ (Figure S8) were analyzed to get the lifetime of photoexcited carriers. The decay time was calculated by using the single exponential function.^{38,39} The TRPL data of film with NaI additive (Figure 4b) shows a longer PL lifetime (831 ns) compared to the control one (583 ns), indicating mitigation of nonradiative recombination with NaI additive.^{40,41}

Furthermore, to investigate the transient photocarrier dynamic, we measured the transient photovoltage (TPV) characteristics for the control and NaI additive devices by modulating V_{OC} with transient illumination, as given in Figure

4c,d. From the analysis of TPV decay curves, the NaI additive device showed a longer carrier lifetime ($\sim 20 \mu\text{s}$) compared to the control device ($\sim 12 \mu\text{s}$), suggesting a reduction in trap-assisted recombination.⁴² These findings correlate with the enhanced performance of the NaI-based device, indicating defect passivation alongside other film characterizations.

3.4. Study of Surface Chemistry Modulation. To further understand the surface chemistry of the synthesized films, X-ray photoelectron spectroscopy (XPS) analysis was conducted. The survey spectra of AgBiI_4 and NaI-incorporated AgBiI_4 are displayed in Figure S9. A set of high-resolution XPS spectra for Ag-3d, Bi 4f, I-3d, and Na-1s are presented in Figure 5a–d. The Ag 3d core level (Figure 5a) exhibits the characteristic peaks at $3d_{3/2}$ (375 eV) and $3d_{5/2}$ (369 eV), with no substantial shift in binding energies between the control and NaI additive AgBiI_4 film. However, in the case of Bi 4f spectra (Figure 5b), XPS shoulder peaks at 162 eV ($4f_{5/2}$) and 156 eV ($4f_{7/2}$) align with the binding energies of metallic Bi^0 , appearing in both control and NaI additive AgBiI_4 films as observed in previous reports.^{38,43,44} The metallic Bi^0 is deleterious for film quality, which contributes to the reductions in efficiency and degradation. We found that metallic Bi^0 peaks are suppressed by 6% in NaI additive films (summarized in Table S5), implying that NaI addition enhances the interaction between the Bi and I atoms. A similar observation has been documented for Ag_3BiI_6 film with the CuBr additive.⁴⁵ A decrease in the metallic Bi may result from the interaction of Na with Bi atoms that are not integrated into the host crystal of the AgBiI_4 film. This interaction enhances surface chemistry, contributing to the improved performance of devices with the NaI additive. The I $3d_{3/2}$ and $3d_{5/2}$ characteristic peaks (Figure 5c) are centered at binding energies of 631 and 619 eV, respectively. Due to the low concentration of NaI, the Na 1s peak appears with low intensity, as shown in Figure 5d. These results corroborate that the NaI additive in the AgBiI_4 film modulates film growth by regulating the morphology and ameliorating surface chemistry, which results in improved device performance.

3.5. Impact of Additive on Device Stability and Film Aging. Moreover, we examine the effect of the NaI additive on the stability of AgBiI_4 solar cells. The time-dependent PCEs of both control and NaI-treated devices are measured in ambient air (temperature: 50–55 °C; relative humidity: 30–40%) without any encapsulation, as shown in Figure 6a. The control AgBiI_4 -based device retains 50% of its initial PCE after 20 h, whereas the NaI-based device retains 77% of its initial PCE after 30 h, showing better stability.

To assess the relation between the device and film stability, we also measured the XRD patterns (Figure 6b,c) of the control film and the NaI additive film, respectively. XRD patterns of freshly prepared film and the aged film (30 days) were compared. Notably, no additional peaks appear in the aged XRD pattern for either the control or NaI-additive-based films, suggesting stable film with the absence of an additional secondary phase over time. A subtle change in the intensity of the dominant peak is observed. The control film shows a slight reduction in peak intensity, while the AgBiI_4 film with the NaI additive almost remains unchanged, indicating that the NaI additive contributes to enhanced film stability. Additionally, the fwhm values for the peaks remain nearly identical between fresh NaI: AgBiI_4 (0.1084) and aged NaI: AgBiI_4 samples (0.1098), further supporting the stability of the AgBiI_4 absorber material under ambient conditions. Despite the

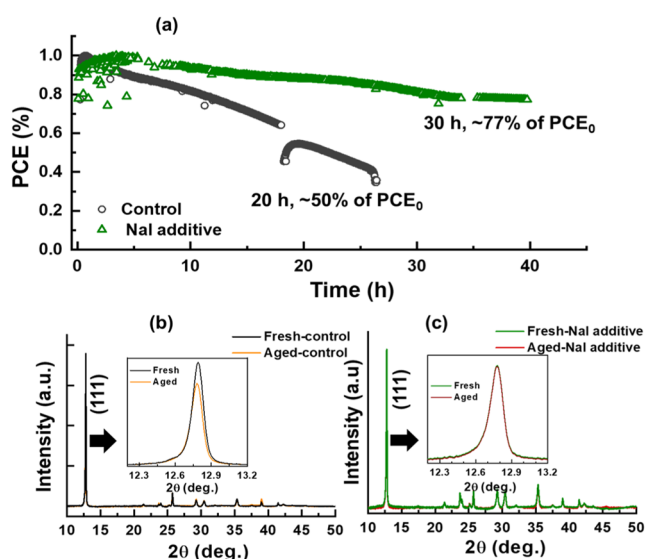


Figure 6. (a) Device stability plots of AgBiI_4 (control and NaI additive)-based solar cell devices. XRD patterns of fresh and aged AgBiI_4 film: (b) control and (c) NaI additive films with the inset of the zoomed-in (111) plane.

structural stability of AgBiI_4 , the observed decline in device efficiency over time suggests other potential degradation factors, such as interactions at the HTL and absorber interface.^{15,46,47}

4. CONCLUSIONS

We investigated the effect of the alkali halide additive in Rudorffite AgBiI_4 -based solar cells. The NaI additive regulates the crystallization of AgBiI_4 crystals and the formation of a highly compact and pinhole-free surface, leading to a significantly improved AgBiI_4 film quality. The film with NaI additive also modulated the surface chemistry of the AgBiI_4 film by quenching the metallic content of Bi^0 ions, as confirmed by XPS analysis. The enhanced film quality led to a significant increase in PCE from 1.33 to 3.72%, accompanied by improved device stability. The TRPL carrier lifetime increased substantially from 583 to 831 ns, indicating more efficient charge transfer, reduced defects, and suppressed carrier recombination, as supported by the TPV decay analysis. These findings highlight that additive engineering is a crucial approach to enhancing the efficiency and stability of AgBiI_4 -based rudorffite solar cells.

■ ASSOCIATED CONTENT

Data Availability Statement

The data that support the findings of this study are available within the article.

Supporting Information

The Supporting Information is available free of charge at <https://pubs.acs.org/doi/10.1021/acsaem.5c00234>.

EDX mapping, XRD patterns analysis, PL spectra, J – V data, device parameters table, reported device data, bandgap estimation, TRPL data, XPS spectra, and stability data (PDF)

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Notes

The authors declare no competing financial interest.

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