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# Blocking Humidity Ingression in $FAPbI_3$ Thin Film for Perovskite Solar Cell Application

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**ABSTRACT**

Owing to the increased global need for renewable energy, cost effect solar energy generation has become key to energy sustainable. Among the new thin film solar cells perovskite solar cells are considered as the suitable alternatives to the market giant c-Si based technology. Among the different perovskites $FAPbI_3$ is the most popular one for their better efficiency, cost-effectiveness, thermal stability, direct bandgap, and improved light absorption compared to other perovskites. However, the commercialization of $FAPbI_3$ is hindered by its phase shift from the photoactive cubic to the photo-inactive hexagonal phase as well as stability issues in humid conditions. This study aims to overcome the limitations of humidity effect on this perovskite layer using a multifunctional additive engineering strategy. 2-Aminoethylthiol was added to the $FAPbI_3$ precursor solution and active layer was spin coated on the pre-cleaned FTO and FTO/$SnO_2$ glass substrates. Through various structural, opto-electronic, and morphological analyses, we found that the additive-modified films showed increased light absorption, photoluminescence emission, and crystallinity by 20%, 400%, and >300%, respectively, promising a higher solar cell current density. The percentage improvements were measured by comparing the peak intensities of the data obtained from the modified film with those obtained from the control film. When these films aged for 200 h at 85% relative humidity and 85 °C temperature, the target film retained photophysical integrity >600% better than the control film, proving their robustness in harsh environments.

**Keywords:** $FAPbI_3$ perovskite, thermal stability, humidity ingression, perovskite solar cell, photophysical properties

## 1. INTRODUCTION

Photovoltaics research has undergone a substantial transformation since the discovery of halide perovskite materials with suitable optoelectronic properties such as low exciton binding energy, direct bandgap, defect tolerance, and high absorption coefficient [1–4]. Perovskite solar cells (PSCs) have recently emerged as a prospective third-generation alternative owing to their rapid advancement and comparable efficiencies to conventional silicon. Since their first trial in 2009, their power conversion efficiency has increased from 3% to over 27% within <15 years [5–7].

Currently, $FAPbI_3$ perovskite demonstrates substantial potential owing to its favorable optoelectronic properties and relatively high efficiency. A significant challenge is posed by its phase instability, particularly its propensity to transition from the favorable cubic (3C) phase to the photo-inactive hexagonal (2H) phase, and subsequently degrade to final $PbI_2$. This process is further accelerated under humid conditions [8,9]. In addition to destabilizing the perovskite structure, water vapor adsorption induces morphological changes, such as a weakening of the grains and an increase in defect density which further impedes the charge-transport pathways of solar cells, potentially leading to a decline in their performance [10,11].

Therefore, understanding and mitigating these effects is critical for the development of perovskite solar technology. As in Table 1, various strategies including compositional engineering, additive assisted modifications, process engineering, and passivation strategies have been utilized in the literature to prevent the unfavorable phase transition [6,7,9]. Incorporating long-chain organic cations or Lewis bases into $FAPbI_3$ precursor solutions has emerged as an effective approach to enhancing its stability. For example, long-chain cations such as phenylethyl ammonium ($PEA^+$) enhance particle size and morphology, thereby potentially improving electronic properties. The hydrophobic properties of these additives establish a moisture-resistant barrier, effectively minimizing the likelihood of phase transitions. In addition to regulating the crystallization process, these compounds are crucial for mitigating the effects of temperature and humidity fluctuations [12–16]. Notwithstanding these endeavors, the humidity resistance and photovoltaic potential of perovskites have not been adequately investigated.

In this study, we utilized 2-Aminoethylthiol (AET) as a novel additive in a perovskite precursor solution and investigated its effect on the structural, optoelectronic, morphological, and stability properties of the perovskite layer.


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**Table 1.** *Comparison of $FAPbI_3$ film properties and stability benchmarks in this study and recent high-impact literature*

| Performance metric | Xiong et al. (2025)[7] | Zhou et al. (2024)[6] | Haris et al. (2023)[9] | This study |
|---|---|---|---|---|
| Material target | Cl-doped $FAPbI_3$ | $FAPbI_3$ (Buried interface) | Pure $FAPbI_3$ | $FAPbI_3$ thin films |
| Primary strategy | Alkali metal oxalates | Benzothiadiazole derivatives | Sulfur heteroatoms (Pb-S) | Multifunctional additives |
| Stability focus | Continuous MPPT / thermal | Ambient storage stability | Water immersion stability | Accelerated damp heat (85/85) |
| Structural effect | Defect passivation | Energy level regulation | 2H to 3C phase shift | >300% Crystallinity increase |
| Optoelectronic gain | Certified 27.2% PCE | Non-radiative suppression | Improved PL lifetime | +400% PL; +20% Absorption |
| Humidity resistance | Not the primary metric | 1000h (Ambient) | Water-stable | 200h at 85% RH / 85 °C |

## 2. METHODOLOGY

The preliminary stage of this investigation entailed meticulous and systematic cleaning of glass substrates. This involved sonication in a soap solution, followed by rinsing with deionized water, acetone, and isopropyl alcohol. The cleaned substrates were treated with ultraviolet (UV)-ozone plasma to eliminate residual organic impurities and enhance their wettability, after which the perovskite precursor solution for $FAPbI_3$ was prepared by dissolving equimolar quantities of suitable precursor components in a N,N-Dimethylformamide-Dimethyl sulfoxide (DMF-DMSO) solvent blend. The solution was agitated at 60 °C for 2 h to produce a transparent precursor solution. Then, it was placed onto the cleaned glass substrates via spin-coating, after which the spin-coated thin films were annealed at 150 °C for 30 min to achieve full crystallization (Figure-1). All processes were conducted inside a glove box. The perovskite films were then characterized using UV-visible (UV-Vis) and photoluminescence (PL) spectroscopy to evaluate their optical characteristics. Furthermore, structural analysis was conducted by performing powder X-ray diffraction (PXRD) and scanning electron microscopy (SEM) to assess the morphology and grain size; the crystallinity and phase purity were also analyzed by PXRD. The acquired data were investigated using Origin software to better understand the film quality. The optimized control and modified perovskite thin films were tested for their humidity resilience and thermal stability by applying 85% RH and 85 °C stresses for 200 h.

## 3. RESULTS AND DISCUSSION

We chose AET as the additive molecule to explore the interaction between the thiol group and the perovskite structure. We prepared the perovskite precursor solution by dissolving synthesized $FAPbI_3$ perovskite powder in a mixed solvent comprising DMF and DMSO in a 4:1 volume ratio. The precursor solution was subsequently spin-coated onto the substrates and annealed at 120 °C for 30 min to finalize the deposition. The additive molecules were immediately integrated into the precursor solution before deposition for additivization. All preparatory procedures were performed in a controlled glove box to preserve material integrity. The deposited perovskite films were later utilized for further characterization.

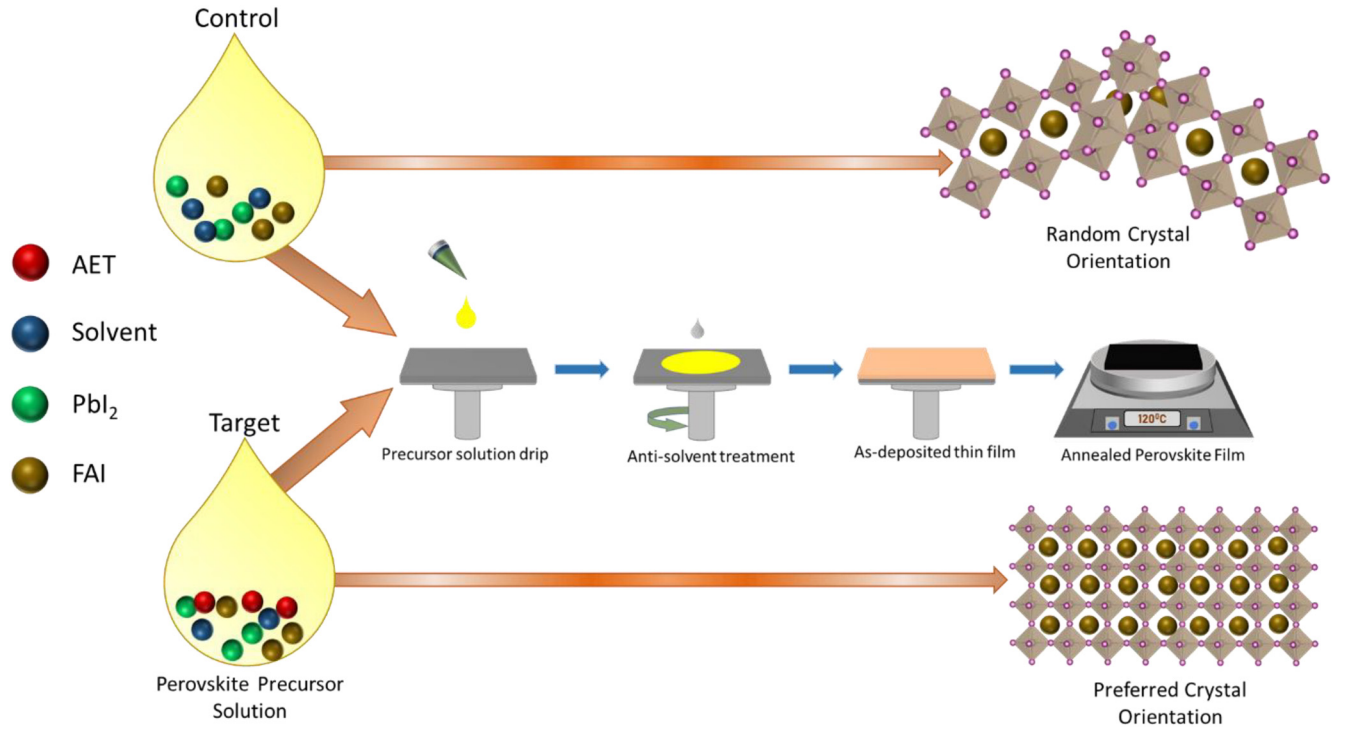



**Figure 1.** Schematic representation of thin film deposition procedure and the impact of the additive on crystal orientation

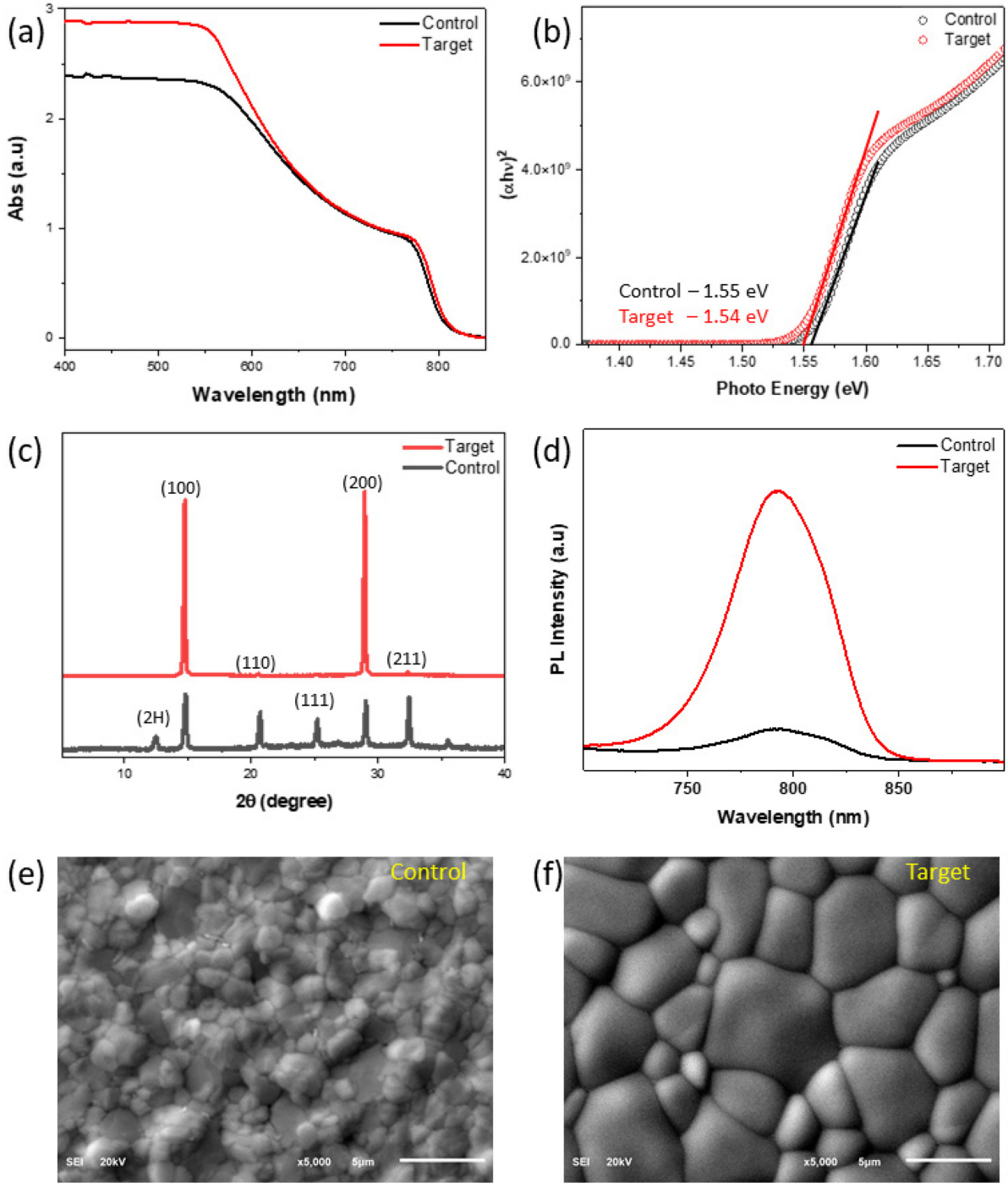



**Figure 2.** (a) UV-Vis absorption spectra of perovskite thin films; (b) tauc plot calculated from UV-Vis transmission spectra for control and target perovskite thin films; (c) PL spectra for control and target perovskite thin films; (d) PXRD reflections for control and target perovskite films; (e) SEM images for control perovskite thin film; (f) SEM images for target perovskite thin films

**3.1. Opto-electronic Analysis.** Improved photophysical characteristics are essential for the development of prospective photovoltaic materials. UV-Vis absorption spectra are essential for clarifying the light-absorption characteristics of a material. We performed measurements on both the control $FAPbI_3$ perovskite thin film (hereinafter referred to as the control) and the additive-modified target perovskite film (hence referred to as the target). Figure 2A shows that the target film had significantly enhanced light absorption in both the visible and UV region compared to the control film. The increase in light absorption is expected to correlate with improved efficiency of solar cells because higher energy conversion is inherently linked to greater light absorption levels[9]. The modifications observed in the UV absorption spectra indicate that the additive modified the structural characteristics of the perovskite, leading to enhanced light absorption efficiency. This modification is a feasible approach to improving the effectiveness of devices utilizing these modified perovskite sheets, which may lead to more efficient energy conversion processes.

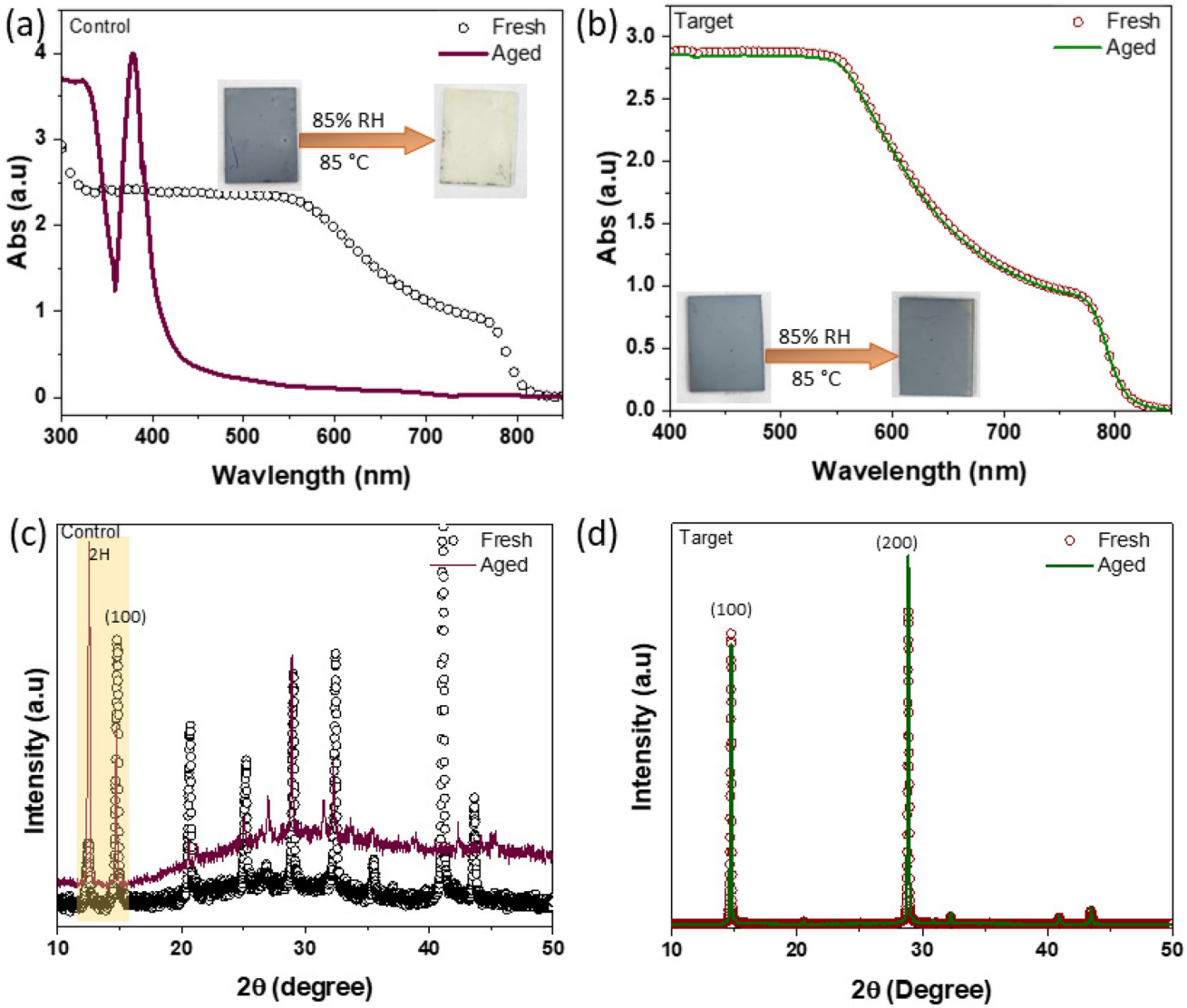



**Figure 3.** (a) UV-Vis spectra recorded before and after stability test for control perovskite film; (b) UV-Vis spectra recorded before and after stability test for target perovskite film; (c) PXRD diffractogram recorded before and after stability test for control perovskite film; (d) PXRD diffractogram recorded before and after stability test for target perovskite thin films

Furthermore, we calculated the optical bandgap of the perovskite layer from tauc plot. As shown in Figure 2B, the bandgap was calculated as 1.55 eV and 1.54 eV for the control and target films, respectively, confirming the absorption of more light by the target film. The literature indicates that the peak intensity of the PL emission in perovskite thin films is significantly influenced by the numerous defects present within the perovskite lattice[6,8,9]. Defects such as vacancies, interstitials, or impurities can create trap states inside the lattice, resulting in nonradiative recombination, which adversely affects the performance of perovskite solar cells. A reduced defect concentration results in less non-radiative recombination and enhanced PL emission. The PL emission spectra obtained from both the control and target perovskite thin films are shown in Figure 2C. The PL emission peak of the control film was observed at approximately 795 nm, whereas the target film displayed an emission peak at approximately 796 nm. Notably, the target film exhibited a substantial increase in PL emission intensity, indicating a large decrease in lattice defects. The improved light absorption, reduced bandgap, and increased PL emission intensity validated the efficacy of our additive engineering approach for use in perovskite solar cells.

**3.2. Structural Evaluation.** Structural studies are key to develop perovskite thin films as they reveal their phase purity, crystal orientation, defect density, and degradation potential. This study employed PXRD to evaluate the structural properties of the perovskite thin films, as shown in Figure 2D. The control perovskite film exhibited most of the perovskite (3C) peaks, indexable to $2\theta$ ~14°(100), 20°(110), 24°(111), 28°(200), and 35°(211). The lower intensities of the (110) and (211) peaks in the target film were due to the AET additive facilitating the transition from random crystal growth to a preferred (h00) orientation. In addition to the perovskite peaks, the control film exhibited another additional peak around $2\theta = 12.8°$, and it is identified for

the presence of a degraded phase of perovskite[9]. This 2H phase is regarded as the non-perovskite phase of $FAPbI_3$, and it has a non-photovoltaic nature; this phase transition is detrimental to the performance of perovskite solar cells. By contrast, the target thin film exhibited highly oriented PXRD reflections with high intensity, indicating excellent crystallinity compared with the control film. Further, it exhibited high-intensity peaks at the (100) and (200) planes, indicating that the modification resulted in highly oriented crystallinity. Moreover, the degraded 2H phase was not visible in the target film. The increased peak intensity and favored (h00) orientation at the macroscopic level indicate an enhancement in crystallinity, potentially resulting from the reduced defect density due to the AET additive.

**3.3. Morphological Analysis.** Furthermore, we analyzed the surface uniformity of the perovskite films using SEM; the recorded surface images are shown in Figure 2 E and F. The control film exhibited a rough surface with smaller grains, and is substantiated by the lower absorption and crystallinity characteristics observed above[4,17]. On the other hand, the target film exhibited a significant enhancement in the grain size and smoothness of the surface. This is in agreement with the enhanced light absorption and crystallinity observed in the UV-Vis and PXRD data explained above.

**3.4. Damp Stability.** In addition, we investigated the effect of our additivation technique on the humidity stability of perovskite layers. To assess this, we obtained digital images, UV-Vis absorption spectra, and PXRD diffractograms before and after the exposure (aging) of both the control and target films to elevated humidity conditions (85% relative humidity) for 200 h, as illustrated in Figure 3 (A to D). The digital image shows that the control film underwent a phase shift to the photoinactive 2H phase (yellow) within several minutes, whereas our target film maintained its photoactive Figure 3C (black) structure even after 200 h of aging at 85% relative humidity. The UV-Vis absorption spectra also substantiate this observation. XRD patterns were acquired for both the fresh and aged materials, enabling a direct comparison of their stability under humid conditions. The results demonstrated no significant formation of the 2H phase characterized by the peak at $2\theta = 11.8°$. In addition, the peak intensities corresponding to the perovskite phase remain stable in the aged films, as shown in Figure 3D. The results highlight the remarkable humidity stability conferred by the additive modification, demonstrating that the structural integrity and performance characteristics of the altered perovskite films were preserved even under adverse environmental conditions[6,9,12]. This tolerance to humidity stress is crucial for practical applications in solar cell technology, as environmental variables may significantly affect device lifetime and performance.

The improved light absorption, increased crystallinity, and remarkable humidity stability of the additive-modified $FAPbI_3$ perovskite films indicate their potential for superior performance in solar applications.

## 4. CONCLUSIONS

In summary, we investigated the impact of the aminoethylthiol molecule as an additive for $FAPbI_3$ perovskite thin films. By applying our additive engineering approach, we were able to enhanced the light absorption properties, crystallinity, and morphology of the perovskite coatings, while also reducing intrinsic defects that could lead to non-radiative recombination. After aging for 200 h, the target perovskite film retained its stability under high humidity (85% RH) and temperature (85 °C). The remarkable stability and robust optoelectronic properties of this perovskite layer render it a promising candidate for application in PSCs. The fabrication and evaluation of PSCs has been not been performed in this study. Future research could focus on investigating the long-term photovoltaic performance and efficiency of these additive-modified $FAPbI_3$ solar cells in fully assembled devices under operational conditions.

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