Improving photostability of perovskite solar cells by interface engineering for emerging applications

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Perovskite materials are receiving growing attention due to their solution processability, outstanding optoelectronic properties, and promising integration capabilities that are comparable to traditional silicon-based materials, showcasing their potentials in photovoltaic and various optoelectronic devices.[1–5] However, the susceptibility of perovskites to environmental factors such as humidity and temperature has inspired most efforts to focus on enhancing thermal and moisture stability of perovskite solar cells (PSCs). Meanwhile, photostability of PSCs, referring to the ability of device materials and interfaces to resist photodegradation, is the key to their practical applications.

Usually, PSCs are fabricated through stacking perovskite and electrode/buffer layer materials, where non-negligible defects within the bulk or at the interfaces of these films can trigger material photodegradation, thereby compromising the device photostability. The multi-layer architecture of PSCs renders their interfaces the most vulnerable sites for photostability. These interfacial regions serve as hotspots for accumulation of defects, which may cause carrier recombination, induce detrimental chemical reactions, and promote ion migration, thereby initiating and accelerating the device degradation under illumination. As such, interface engineering has developed for addressing photostability challenges by passivating interfacial defects, optimizing energy-level alignment, and establishing barriers against ion migration in PSCs. These approaches facilitate efficient carrier extraction and transportation, offering a vital pathway to enhance the photovoltaic performance and photostability of PSCs simultaneously.[1] Hence, this perspective aims to elucidate main photodegradation mechanisms of PSCs and emphatically summarize the critical role of interface engineering in improving device photostability. Meanwhile, potential applications of PSCs are also discussed, along with insights into upcoming research directions and challenges in this new-generation photovoltaic technology (Figure 1).

PHOTODEGRADATION MECHANISMS

The photo-instability of PSCs primarily originates from two kinds of degradation mechanisms, including photo-induced ion migration and destructive effects of ultraviolet (UV) light. For one thing, the unique "soft lattice" characteristic of perovskites under illumination allows for substantial migration of ions, such as halide anions (*e.g.*, Cl^- and I^-) as well as methylammonium (MA^+) and formamidinium (FA^+) cations. This photo-induced ion migration leads to phase segregation in mixed-halide perovskites, adversely influencing the overall performance and stability of PSCs. And ions can migrate along grain boundaries or interfacial defects in the perovskite films, eventually reaching charge transport layers or electrodes and causing irreversible performance degradation. For another, UV light within the solar spectrum poses the greatest threat to the stability of PSCs. Typical inorganic electron-transporting layers (ETLs), such as TiO_2 and SnO_2, can absorb UV light and catalyze degradation of the perovskite by generating free radicals and activating vacancies, leading to the breaking of chemical bonds within the perovskite layer of PSCs and further reducing their power conversion efficiencies (PCEs). Furthermore, UV light may trigger side reactions at the interface between the perovskite and charge transport layers, creating unstable intermediates that accelerate the photodegradation of PSCs.

Given that these photodegradation mechanisms are closely linked to interfaces, the research focus on the photostability of PSCs has transitioned from early efforts in optimization of bulk perovskite materials to precise manipulation of their surfaces/interfaces. Under operational conditions involving light, humidity, and heat, the surfaces and interfaces of perovskites, acting as terminal regions of the crystal lattice and thus holding numerous dangling bonds-induced defects, are hotspots for ion migration and defect accumulation. Consequently, interface engineering is expected for simultaneously passivating surface/interface defects and suppressing ion migration, thereby addressing the photostability challenges in PSCs.

INTERFACE ENGINEERING STRATEGIES

Previous studies have mainly achieved static protection of these interfaces in PSCs by the use of chemical passivators such as alkali metal halides and Lewis acids/bases, adoption of functional molecular interlayers, and construction of heterojunctions or blocking layers. These strategies have laid a crucial foundation for improving initial device performance and photostability of PSCs. However, under practical conditions such as continuous illumination, the persistent generation of new defects and the occurrence of photo-induced interfacial delamination undermine the effectiveness of purely static defect passivation, thereby limiting the realization of long-term stability.

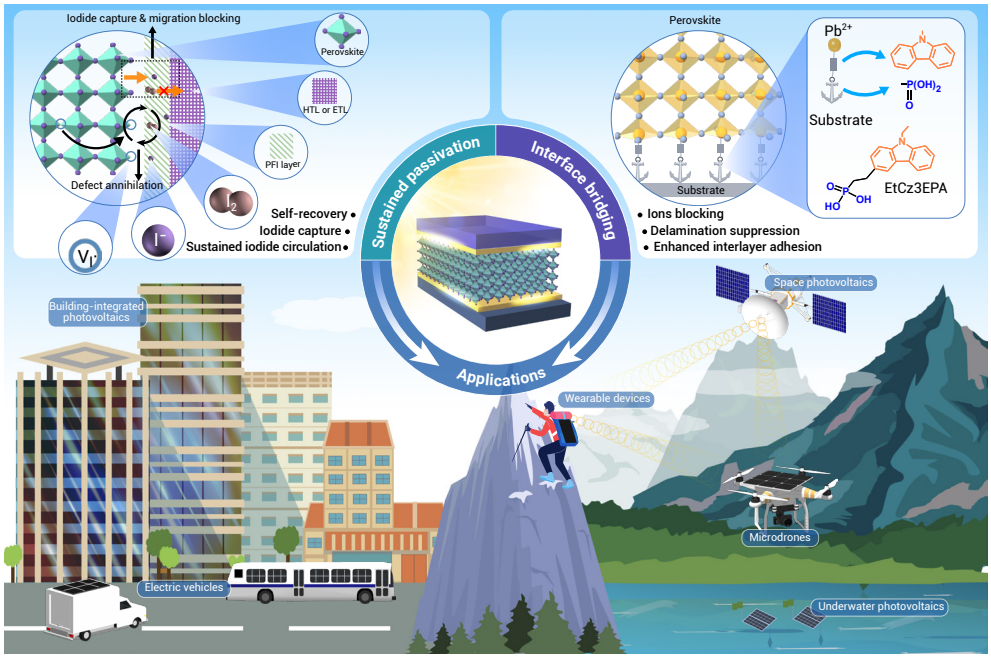

Figure 1. Improved photostability of PSCs by interface engineering towards potential applications
Top: schematic of sustained passivation—a dynamic strategy in which an interlayer actively captures and blocks mobile iodide ions, and illustration of interface bridging—a structural reinforcement strategy wherein SAM molecules act as chemical anchors to enhance interface adhesion and suppress delamination. Bottom: emerging applications of PSCs.

Recently, the dynamic interface strategy aims to endow the interface of perovskites with an "active-healing" capability. This sustained interface passivation was achieved by adopting perfluorodecyl iodide (PFI) as a multifunctional interlayer in PSCs.[2] As shown in Figure 1, the PFI utilizes its strong iodine affinity through directional halogen bonding to capture harmful iodide species (such as I^- and I_2) generated by photolysis, thus confining them at the interface and preventing their migration to the hole-transporting layer (HTL). Crucially, this process facilitates a sustainable, closed-loop iodide circulation system that enables defect annihilation. Iodine vacancies ($V_i^{\cdot}$) can migrate and then recombine with the captured iodide species, completing a dynamic cycle that provides an active defect-healing function. The efficacy of this strategy is demonstrated by the exceptional photostability of the PFI-incorporated PSCs, which has retained 85% of their initial PCEs after harsh UV aging for exceeding 300 h. And also, such PSCs maintained 90% of their initial PCEs after 1,500 h of continues solar illumination, exhibiting the greatly improved stability with a ~30-fold increase in the lifetime compared to the control device without a PFI interlayer.

In addition to dynamic interface passivation, interfacial mechanical reinforcement is expected to resolve the physical structure fragility of PSCs. UV light can disrupt chemical bonds in organic materials to generate charge-trapping defects, which are particularly problematic at the interface between the perovskite layer and organic charge transport layers, leading to delamination between diverse layers after the prolonged light exposure. As displayed in Figure 1, the interface between the perovskite layer and the organic HTLs such as poly(triarylamine) (PTAA), is typically held together only by weak van der Waals forces, making it susceptible to delamination under continuous illumination and thermal stress. To overcome this limitation, a novel bifunctional self-assembled monolayer (SAM) molecule, [2-(9-ethyl-9H-carbazol-3-yl)ethyl]phosphonic acid (EtCz3EPA), has been developed to achieve interface bridging.[3] This molecule firmly anchors the perovskite layer to the transparent oxide electrode substrate through strong, bidirectional chemical bonds. Such robust bonding not only physically suppresses ion migration and improves interface adhesion, but also plays a crucial role in mitigating UV light-induced photodegradation by stabilizing the buried perovskite/HTL interface. As a result, PSCs employing this hybrid EtCz3EPA/PTAA HTL exhibited a T_{90} lifetime of 1,780 h under illumination with a light emitting plasma lamp (~3.5% UV), while a corresponding mini-module also retained a high PCE over 16% among champion minimodules after 29 weeks of outdoor testing.

PROMISSING APPLICATIONS

Currently, PSCs are leveraging their salient advantages of lightweight, flexibility, and high PCEs to showcase significant potential across a range of applications beyond conventional photovoltaics (Figure 1). For applications in building-integrated photovoltaics (BIPV), opaque and semitransparent PSCs can be seamlessly incorporated into architectural designs, serving as efficient power-generating units and aesthetic components. For electric vehicles, flexible PSCs enable conformal integration with the bodywork to provide auxiliary power and extend driving range. In the realm of portable electronics, ranging from wearable power sources to long-endurance microdrones, PSCs offer a promising solution to overcome battery life constraints. Furthermore, PSCs are being explored for utilizations in extreme environments such as space and underwater settings, where conventional photovoltaic technologies may face limitations. For space applications, combination of the high-performance power generation, excellent stability, low cost, and radiation resistance in PSCs can significantly reduce launch payloads and operating costs of spacecrafts. However, space missions impose stringent stability requirements, including resistance to proton/electron irradiation, thermal cycling, and high vacuum. Thus, the robust interface design in PSCs is critical for sustaining device performance over extended mission lifetime. In the domain of oceanic exploration, although water selectively absorbs and scatters most long-wavelength light in the solar spectrum, short-wavelength blue light can penetrate into the deepest and be absorbed by PSCs. The tunable bandgap of perovskites allows for effective photo-response to this specific spectral region, making PSCs a suitable option for underwater photovoltaics.[4] Nevertheless, underwater operation also requires strong interfacial resistance of PSCs to moisture and ion penetration, underscoring the necessity of interface engineering that integrates hydrophobic passivation interlayers with excellent optical transparency. To bridge the gap between laboratory exploration and commercial viability of PSCs, it is imperative that they overcome the fundamental bottleneck of stability. Current approaches rely heavily on complex external encapsulation to ensure long-term stability under multiple environmental stressors. This reliance increases manufacturing complexity and cost. Enhancing intrinsic photostability of PSCs can reduce the demand for such high-barrier encapsulation, thus simplifying fabrication processes and lowering production costs. Importantly, it facilitates the use of thin, flexible encapsulation layers, preserving the inherent lightweight and mechanical flexibility of PSCs and enabling better design versatility for applications in wearable electronics and flexible photovoltaics.

CONCLUSION AND OUTLOOK

In summary, interface engineering provides feasible solutions to primary challenges constraining the photostability of PSCs, namely photo-induced ion migration and degradation. Its strategies have evolved from traditional defect passivation to recent methods involving sustained interface passivation and interface bridging. These pathways significantly enhance the photostability of PSCs and lay the foundation for long-term reliability. Thus, photostable PSCs are good candidates for promising applications spanning outdoor lighting, smart buildings, portable electronics, and even power systems for underwater and space environments. As PSCs advance towards large-area module fabrication, scaling interface engineering strategies from laboratory to industrial production poses critical challenges related to long-term stability.[5] Dynamic interface engineering requires precise nanometer-scale control of layer thickness, remaining a challenge for scalable deposition techniques. Furthermore, while interfacial reinforcement can prevent delamination, excessive interface bridging may induce rigid stress concentration points which increase the risk of mechanical failure such as microcracks under thermal cycling and thus create new pathways for degradation. Therefore, future progress critically hinges on developing scalable and universal interface strategies that ensure bankable long-term operation stability of the PSC-based photovoltaic technology while proactively mitigating its lead toxicity risks. Ongoing advancements in interface engineering are expected to assist PSCs overcome commercialization barriers in the future.

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AUTHOR CONTRIBUTIONS

Z. Y. proposed the idea and supervised the project. K. S. and Z. Y. designed the manuscript. P. W. provided insightful suggestions. All authors contributed to the manuscript and approved the final version.

DECLARATION OF INTERESTS

The authors declare no competing interests.