

Development and Future Prospects of Perovskite Solar Cells

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Abstract: Perovskite solar cells (PSCs), as a representative of third-generation photovoltaic technology, have emerged as a research hotspot for overcoming the performance limitations of traditional silicon-based cells due to their high photoelectric conversion efficiency, low cost, and structural design flexibility. This paper systematically reviews breakthrough advancements in PSCs over the past five years: the efficiency of single-junction cells has risen from 25% to 26.9%, while tandem cells have achieved efficiencies exceeding 33.89%. Through material engineering (compositional regulation, defect passivation), interface optimization (alloyed electrodes, passivation layers), and encapsulation techniques (flexible stress-release structures, eco-friendly recycling), the stability under damp-heat conditions (T80 lifespan exceeding 2,000 hours) and environmental adaptability of PSCs have been significantly enhanced. Concurrently, advancements in large-area printing and vapor deposition technologies have accelerated industrialization (module efficiency of 28.6%, GW-scale production lines established). However, challenges such as lead toxicity concerns, insufficient long-term stability, and efficiency degradation in scaled-up production remain critical barriers to commercialization. Looking ahead, the development of lead-free materials, quantum dot-based triple-junction architectures, and closed-loop recycling systems could propel PSCs toward a 40% efficiency target, positioning them as a core driver of photovoltaic industry innovation under the "Dual Carbon" strategy.

Keywords: Perovskite Solar Cells (PSCs), Photoelectric Conversion Efficiency (PCE), Stability, Lead-free Perovskite, Large-area Fabrication

1. Introduction

In recent years, the global development of new energy has been vigorously promoted. Solar cells, as an ideal supplement and alternative to non-renewable energy, have attracted widespread attention, leading to the rapid development of the photovoltaic industry and an increasing demand for production capacity. However, to achieve the widespread application of photovoltaic products and make solar energy a primary source of power, there are still many challenges. These include high material costs, significant losses, low efficiency, and pollution caused by the preparation process. Current solutions mainly focus on replacing materials to reduce costs, improving photoelectric conversion efficiency, and enhancing cost-effectiveness.

The development of solar energy can be roughly divided into three stages. The first stage used high-purity silicon as the raw material, which had the disadvantage of high cost and energy consumption. The second stage adopted thin-film solar cells, but large-scale production resulted in environmental pollution and high manufacturing costs. Therefore, how to further improve

photoelectric conversion efficiency and reduce production costs has become the main research direction for third-generation solar cells.

In 2013, Oxford University in the UK invented a perovskite solar cell that uses organic metal halide perovskite structures as light-absorbing materials. Since then, perovskite solar cells have developed rapidly, with efficiency rising from 3% to 19.3% in just eight years. In comparison, researchers spent 23 years improving the efficiency of dye-sensitized solar cells, also considered third-generation, from 7.9% to 13%. Moreover, perovskite solar cells exhibit an extremely high extinction coefficient and strong light absorption capacity, which gives them excellent development prospects.

This paper will discuss recent advancements in perovskite solar cells from three aspects: breakthroughs in photoelectric conversion efficiency, improvements in stability, and large-scale production. It will analyze their core advantages and the challenges currently faced, as well as offer a future outlook.

2. Development of Perovskite Solar Cells

2.1. Photoelectric Conversion Efficiency

The photoelectric conversion efficiency of solar cells is one of their most important parameters. Perovskite Solar Cells (PSCs) have been a highly notable breakthrough in the photovoltaic field in recent years. Their efficiency has rapidly increased from 3.8% when first reported in 2009 to 22.7% in 2017 (with the highest laboratory efficiency now exceeding 26%), a development pace far surpassing that of traditional silicon-based solar cells, which took decades. This leap forward is attributed to the synergistic innovation in materials science, device engineering, and process optimization.

The efficiency of single-junction solar cells has been continually improved through innovation. The theoretical limit of efficiency is about 33%, but in practice, due to material bandgaps and spectral response range limitations, 25% is regarded as the critical point approaching the practical process limit. In 2019, the KRICT team successfully addressed the defects and phase transition challenges in perovskite films through crystallization control using long-chain alkyl ammonium chloride and in-situ process optimization, ultimately breaking through the 25% critical point, opening new avenues for the development of perovskite solar cells. In practical applications, perovskite solar cells are divided into single-junction cells and tandem cells, each with its unique areas of advantage.

2.1.1. Single-Junction Cells: Breakthrough from 25% to 26%

The SEO team from the Korea Institute of Energy Research used FTO to replace ITO and SnO₂, employing chemical bath deposition (CBD) instead of c-TiO₂/mp-TiO₂ [1]. To reduce light loss, the textured surface of FTO was used to scatter incident radiation and capture light by increasing the optical path length. In terms of composition, FAPbI₃ and MAPbBr₃ (0.8 mol%) containing MACl (approximately 35 mol%) and excess PbI₂ (9 mol%) were used to improve the optoelectronic performance of large grain sizes, as shown in Figure 1. This enabled the photoelectric conversion efficiency to exceed the 25% threshold. This study not only achieved innovation in material design but also provided an important theoretical foundation for subsequent perovskite cell optimizations. Since then, other global teams have also reported breakthroughs in the photoelectric conversion efficiency of single-junction perovskite solar cells.

The team from the Chinese Academy of Sciences introduced a porous insulating layer with random nanoscale openings about 100 nanometers thick and performed drift-diffusion simulations on this porous insulator contact (PIC) [2]. By controlling the growth mode of alumina nanosheets using a solution process, they achieved an efficiency of up to 25.5% in p-i-n devices by using PIC to reduce

the contact area by about 25%, as shown in Figure 2. This breakthrough marks a significant advancement in structural design for perovskite solar cells, offering new ideas for achieving higher efficiencies.

The University of Science and Technology of China, where the research team introduced a bifunctional ligand, 2- (methylthio) ethylamine hydrochloride (METEAM), into the perovskite precursor solution [3]. This improved the (100) orientation of the perovskite crystals and enhanced the buried interface. The METEAM molecules preferentially adsorb onto the (100) crystal face of the perovskite due to strong interaction with the perovskite lattice, inducing directional crystallization. Meanwhile, METEAM molecules spontaneously aggregate at the buried interface, acting as a bridge between the perovskite and the tin oxide (SnO_2) electron transport layer, passivating defects in both directions and significantly improving the photoelectric conversion efficiency of the cells, demonstrating the immense potential of material engineering.

Higher Photoelectric Conversion Efficiency - Chen Junchao et al. [4], introduced additional conjugated groups into the carbazole units of 4PACz, developing an asymmetric self-assembled monolayer (SAM) known as 4PABCz. This molecule forms a compactly assembled, upward-facing hole transport layer (HTLs), achieving dense coverage and efficient hole extraction on the substrate. Additionally, the unique configuration of the substrate covered by 4PABCz effectively regulates the crystallization of the perovskite thin film and releases residual stress. Consequently, an inverted perovskite solar cell on an FTO substrate achieved a maximum photoelectric conversion efficiency of 26.90%, as shown in Figure 3.

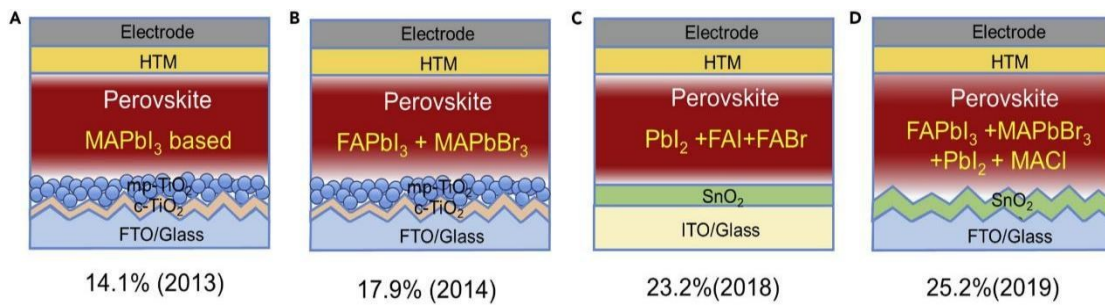


Figure 1: Structural Evolution and Efficiency Improvement of Perovskite Solar Cells from 2013 to 2019.

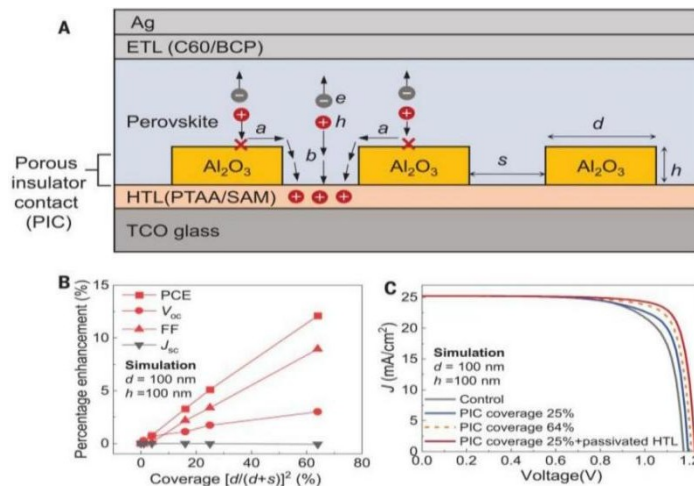


Figure 2: Experimental and Simulation Results of Structural and Performance Optimization via Porous Insulator Contact (PIC).

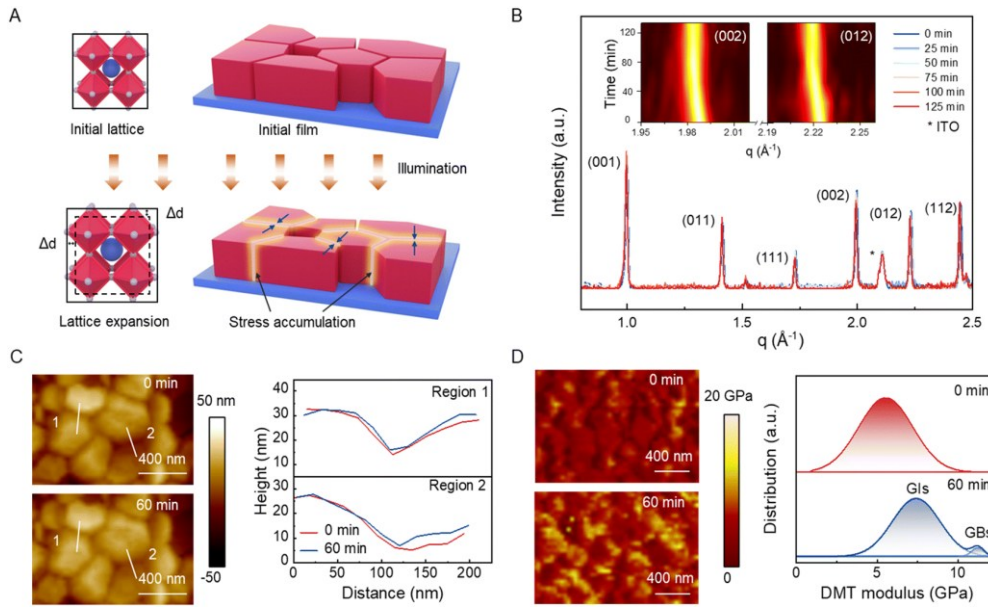


Figure 3: Structural and Performance Evolution of Perovskite Solar Cells Under Light Illumination.

2.1.2. Tandem Solar Cells: A Milestone from 29% to 35%

Tandem perovskite solar cells achieve a broader absorption of the solar spectrum through a multi-layer structure. Each layer of material has a different bandgap, allowing it to absorb photons within specific wavelength ranges, thereby improving the overall photovoltaic conversion efficiency. A single-junction cell can typically only absorb solar light within a specific wavelength range effectively, while tandem cells, with their material layers of different bandgaps, can absorb a broader solar spectrum. This increases the utilization of light energy and reduces energy loss. Despite the late start of tandem perovskite solar cell research, it has received widespread attention and research.

Early studies mainly focused on building theoretical models and experimental verification of small-area devices. With ongoing technological advancements, the efficiency of tandem cells has gradually improved, achieving significant results in laboratory environments. In recent years, with breakthroughs in materials science and device engineering, the efficiency of tandem perovskite solar cells has surpassed 30%, making it one of the research hotspots in the photovoltaic field.

In 2020, A. Al-Ashouri et al. stabilized a perovskite with a 1.68 eV bandgap using a self-assembled monolayer structure [5]. This monolayer structure serves as an effective hole-selective contact, minimizing non-radiative carrier recombination. In unencapsulated air, the tandem silicon cells maintained 95% of their initial power conversion efficiency after 300 hours of operation 29%. As shown in Figure 4, this study brought the efficiency of tandem perovskite solar cells close to 30%, providing a theoretical foundation for subsequent breakthroughs in this threshold.

In 2023, X.Y. Chin and colleagues used a combination of experimental and computational methods to optimize the interfaces in tandem solar cells [6]. They applied atomic layer deposition (ALD) to form a thin layer of aluminum oxide (Al_2O_3) at the perovskite/silicon interface, which helped passivate defects and improve charge transport. Record efficiency of 31.25% for perovskite/silicon tandem solar cells. The breakthrough of 30% conversion efficiency marks a significant advancement in tandem perovskite cells, providing new ideas for further efficiency improvements.

In 2024, Longi et al. designed a dual-layer intertwined passivation strategy by utilizing lithium fluoride ultrathin films with a nano-scale discrete distribution [7], followed by the additional deposition of diammonium iodide molecules. This strategy combines efficient electron extraction with further suppression of non-radiative recombination. The resulting perovskite/silicon tandem

cells achieved an independently certified stable power conversion efficiency of 33.89%, with a fill factor of 83.0% and an open-circuit voltage close to 1.97 V, as shown in Figure 5.

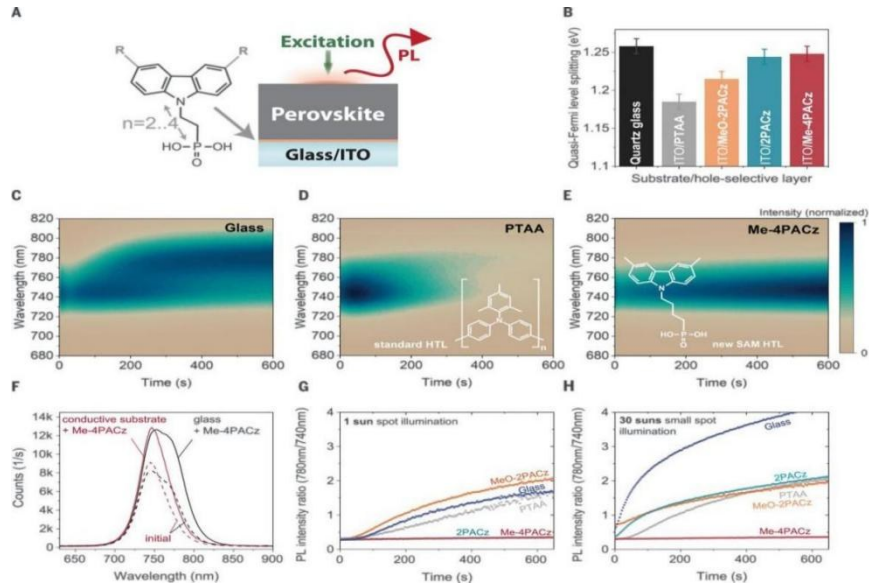


Figure 4: Optical Properties of Perovskite Materials Under Different Substrates and Conditions.

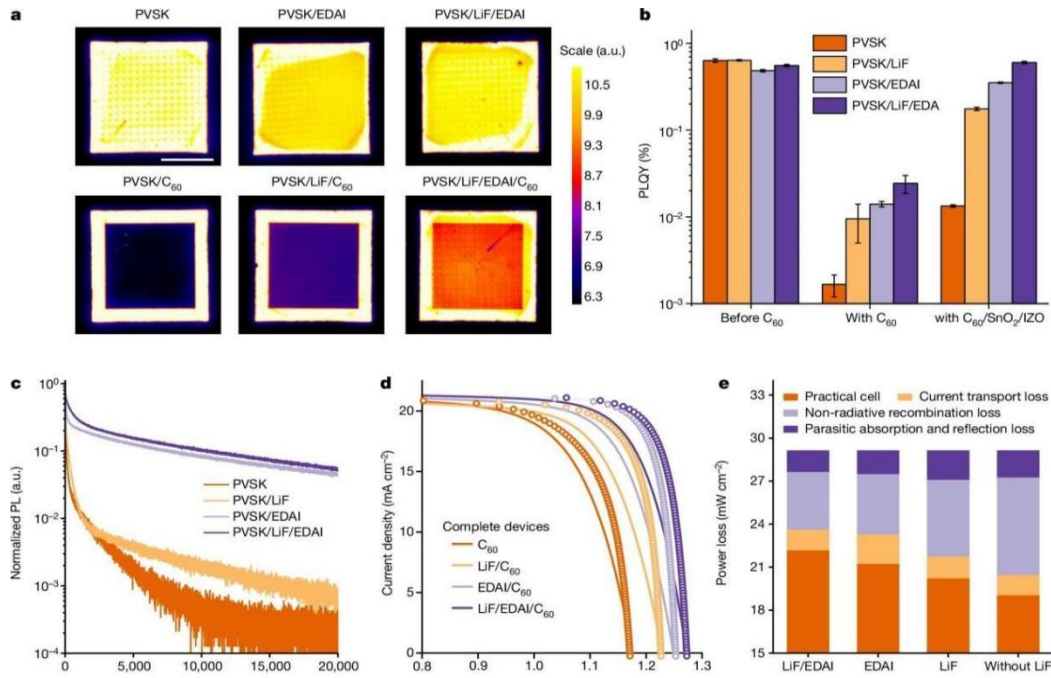


Figure 5: Optical Properties, Device Performance, and Power Loss Analysis of Perovskite Solar Cells Modified with LiF and EDAI.

2.2. Stability

Stability is a key factor in the application of tandem perovskite solar cells, influenced by various factors.

Material aspects: The gaps, vacancies, and impurity defects in perovskite act as recombination centers, causing non-radiative charge recombination and accelerating device degradation.

Furthermore, the halide phase separation in the battery under continuous illumination limits the lifespan of the battery.

Environmental factors: Light exposure and high-temperature environments accelerate the degradation of perovskite materials. High humidity can cause moisture to enter the material, leading to degradation and performance decline. To address these issues, researchers mainly focus on optimizing material engineering, interface engineering, and encapsulation technology.

2.2.1. Material Engineering: Component Regulation and Defect Passivation

Material engineering improves the intrinsic stability of materials by optimizing the components of perovskite, introducing dopants, or using novel material systems.

Lead-free perovskite component optimization: The team of Wang Chuan and Liu Shengzhong from Shaanxi Normal University developed a surface chemical reconstruction strategy based on the Finkelstein reaction [8]. As shown in Figure 6, this method uses benzyl chloride methyl sulfide (BCMS) molecules to induce the formation of a stable phase on the surface of inorganic perovskite ($\text{CsPbI}_{3-x}\text{Br}_x$). The method substitutes chlorine ions for iodine defect sites, significantly reducing defect state density, and improving the power conversion efficiency (PCE) of trans-cis inorganic perovskite solar cells to 20.82%. After continuous illumination for 3000 hours, the efficiency remained at 90% of the initial efficiency. Additionally, bismuth-based lead-free perovskites (such as $\text{Cs}_3\text{Bi}_2\text{I}_9$) achieved an extended T80 lifetime of 2000 hours under hot and humid conditions (85°C/85% RH), with an efficiency degradation rate of less than 3%.

Secondary phase stabilization strategy: The research team of You Jingbi from the Institute of Semiconductors, Chinese Academy of Sciences, published a study in Science where they introduced rubidium chloride (RbCl) into the perovskite, transforming the unstable secondary phase PbI_2 into a thermally and chemically stable $(\text{PbI}_2)_2\text{RbCl}$ (PIRC). This strategy increased the ionic migration barrier of the perovskite material by three times, maintaining 80% of the initial efficiency under accelerated aging at 85°C. The certified efficiency reached 25.6% [9].

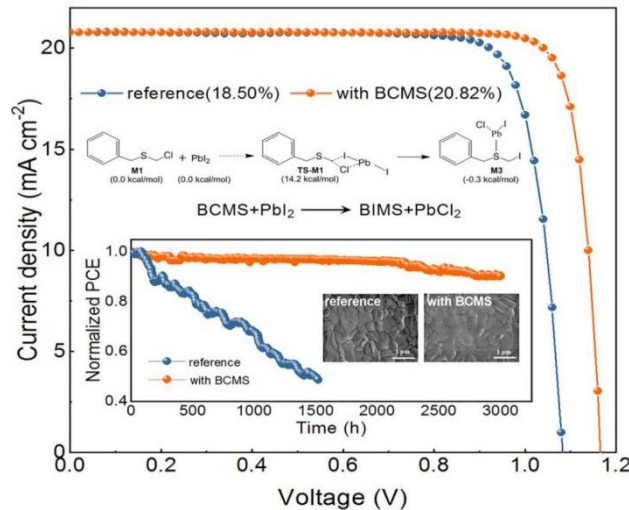


Figure 6: Experimental Results of Perovskite Solar Cell Performance Optimization via BCMS Additive [8]

2.2.2. Interface Engineering: Defect Passivation and Charge Transport Optimization

Interface engineering reduces interface defects and suppresses non-radiative recombination by optimizing charge transport layers, introducing passivation layers, or constructing heterojunctions.

Alloy electrode and graphene barrier layer: As shown in Figure 7, the team of Han Liyuan from Shanghai Jiao Tong University proposed a copper-nickel alloy electrode and used in-situ growth of graphene on both sides of the electrode to form a physical barrier layer, effectively inhibiting perovskite decomposition and ion migration. The battery based on this electrode maintained nearly no degradation in efficiency after 5000 hours of continuous illumination, while achieving efficiency exceeding 24% [10].

Surface passivation and energy level alignment: The teams of Yang Yang from the University of California, Los Angeles (UCLA) and Wang Rui from Westlake University reported in Nature a novel surface treatment strategy. This strategy involves replacing traditional halide anions with organic anions to reduce surface potential shift. The strategy ensured that the perovskite solar cells retained 87% of their efficiency after 2000 hours of accelerated aging, with a PCE of 24.4% [11].

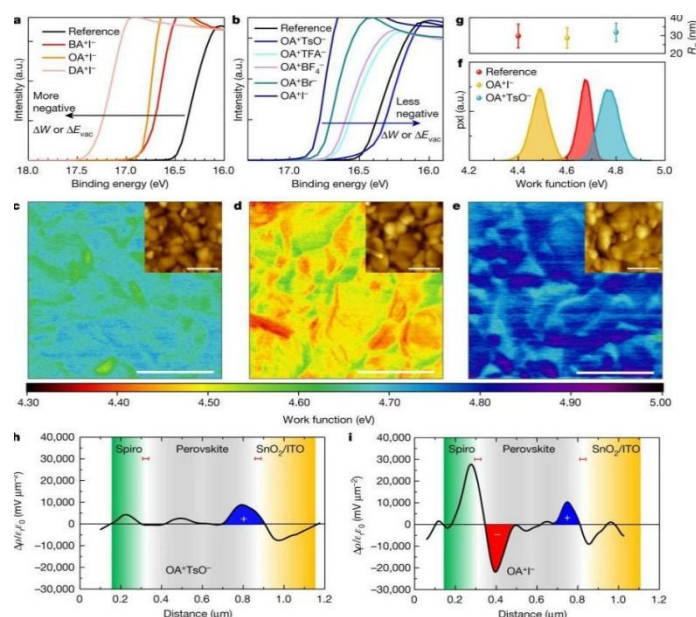


Figure 7: Impact of Additive Treatments on Interfacial Properties and Performance of Perovskite Solar Cells: Insights from Photoelectron Spectroscopy, Morphological Imaging, Work Function Distribution, and Potential Changes.

2.2.3. Encapsulation Technology: Environmental Isolation and Stress Relief

Encapsulation technology extends the lifespan of devices by physically isolating external environments (such as moisture and oxygen) and relieving mechanical stress.

Stress-relief layer for flexible devices: The team of Chang Jingjing from Xidian University introduced an octyl acetamide (OAAc) thin film as a stress-relief layer for flexible perovskite solar cells, reducing residual stress through intermolecular forces. After 8000 bending cycles at a 5mm radius, the flexible device retained 74% of its initial efficiency, while the hydrophobic alkyl chains enhanced moisture resistance, as shown in Figure 8 [12].

Water-based solvent recyclable encapsulation: The team from Linköping University in Sweden proposed an environmentally friendly encapsulation recycling technique in Nature, using a water-based solvent to dissolve the encapsulation layer and separate the active layer. The recycled battery achieved efficiency comparable to the original device, providing an industrial pathway for the recycling of perovskite solar cells.

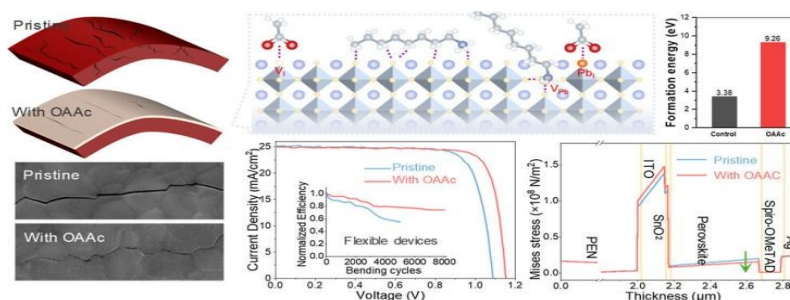


Figure 8: Performance Optimization of Perovskite Solar Cells via Introduction of OAAc [12].

2.3. Large-area Fabrication Technology

Since traditional photovoltaic material technology is already quite mature and cost-controlled, the ability to scale up new solar cell technologies to industrial-level large-area production is crucial.

2.3.1. Printing Process: From Laboratory to Production Line

Fina Photovoltaics achieved a module efficiency of 15.3% for a 20×20 cm module with an annual production capacity of 100 MW and a material utilization rate of 80%. This study demonstrates the application potential of the doctor blade method in large-area fabrication, providing an important technological foundation for industrialization.

HZB (Helmholtz-Zentrum Berlin) developed a 30×30 cm flexible module with an efficiency of 18.1%, applied in automotive photovoltaic rooftops. This study demonstrates the application potential of inkjet printing technology in flexible photovoltaic modules, providing a new technological path for flexible photovoltaic applications.

2.3.2. Vapor Deposition: Environmental Protection and Uniformity

GCL-Poly and NREL (National Renewable Energy Laboratory) prepared a 0.72 m² module with an efficiency of 18.6%, using a solvent-free process that meets environmental protection standards. This study demonstrates the application potential of vapor deposition technology in large-area fabrication, providing new technological means for environmentally friendly and efficient production.

2.3.3. Commercialization Cases

100 MW Perovskite/Silicon Tandem Production Line: The module efficiency reached 28.6%, with a lifespan of 25 years. This case demonstrates the commercialization potential of perovskite/silicon tandem solar cells, providing a solid technological foundation for large-scale applications.

10 GW Base Launch: The target cost is less than \$0.1/W. This case highlights the potential of perovskite solar cells in cost control and large-scale production, providing an important economic foundation for industrialization.

3. Core Advantages of Perovskite Solar Cells in the Last Five Years

3.1. Advantages of Material Properties

High Light Absorption Coefficient (10^5 cm^{-1}): A thickness of just 200 nm can absorb the entire light spectrum, much thinner than silicon (200 μm). This characteristic gives perovskite solar cells a significant advantage in terms of material usage and manufacturing costs.

Tunable Bandgap (1.2-2.3 eV): The Sn/Pb ratio and halogen doping allow for flexible matching to stacked-layer requirements. This characteristic gives perovskite solar cells great potential in stacked applications, enabling higher photovoltaic conversion efficiency.

3.2. Flexibility in Structural Design

Stacked-Layer Compatibility: Seamlessly integrates with silicon, CIGS, and organic solar cells, with theoretical efficiency exceeding 40%. This characteristic gives perovskite solar cells significant application potential in multilayer structures, allowing for higher photovoltaic conversion efficiency.

Flexibility for Applications: Can be printed on plastic and metal foils, extending to wearable and building-integrated photovoltaics (BIPV). This characteristic gives perovskite solar cells enormous potential in flexible photovoltaic applications, enabling a wider range of use scenarios.

3.3. Economic Viability in Processing

Low-Temperature Fabrication (<150°C): Energy consumption is only 1/10th of that of silicon, and it is compatible with roll-to-roll (R2R) mass production [13]. This characteristic gives perovskite solar cells a significant advantage in terms of manufacturing costs and energy consumption, enabling large-scale production and application.

Low Raw Material Costs: Lead iodide costs as little as \$1 per kg, with material costs accounting for less than 5%. This characteristic gives perovskite solar cells a significant advantage in terms of material costs, allowing for lower production costs.

4. Current Challenges and Solutions

4.1. Stability and Lifespan

For common perovskite solar cells, their intrinsic material properties cause phase separation under humid heat and ultraviolet light, while ion migration leads to efficiency degradation. This issue seriously affects the long-term stability of perovskite solar cells and limits their large-scale application. Extensive research has been conducted to address this, with mainstream solutions mainly focusing on developing fully inorganic perovskites (such as CsPbI₂Br) and self-healing encapsulation materials. The introduction of fully inorganic perovskites and self-healing materials significantly improves the stability and lifespan of the cells.

More importantly, analysis of the degradation mechanisms of perovskite solar cells has been conducted, incorporating in-situ characterization technologies (such as synchrotron X-ray) to analyze degradation mechanisms. By using in-situ characterization techniques, the degradation mechanisms of perovskite cells can be deeply analyzed, providing a scientific basis for addressing stability issues.

4.2. Lead Toxicity Controversy

Lead in perovskites has high bioaccumulation and long-term toxicity, potentially entering the food chain through water and soil, harming ecosystems and human health (such as causing neurological damage). Its toxicity and potential environmental risks significantly impact the public acceptability of perovskite solar cells, limiting their large-scale adoption. To address this, lead sequestration technologies (such as zirconium phosphate adsorption layers, with leakage <0.01 g/m²) have been employed. The introduction of lead sequestration technologies significantly reduces the risk of lead leakage, improving the environmental safety of perovskite solar cells.

Additionally, current research into bismuth-based (Bi) and tin-based (Sn) lead-free perovskite cells has reached efficiencies of 12-18%. By developing lead-free perovskite materials, the use of lead is significantly reduced, enhancing the environmental friendliness of perovskite solar cells.

4.3. Mass Production Bottlenecks

Large-area modules currently cause significant efficiency losses (e.g., a 5-10% drop in efficiency for modules larger than 20 cm²). This issue severely impacts the large-scale production and application of perovskite solar cells, limiting their market competitiveness. To address this, efforts have been made to optimize the uniformity of film thickness in doctor blade/spray coating processes (CV <5%). By optimizing the fabrication process, significant improvements in efficiency and uniformity for large-area modules can be achieved, reducing efficiency losses. High-speed vapor deposition equipment (such as Coexin nanowires, with speeds up to 10 m/min) is also being developed. The development of high-speed production equipment significantly improves production efficiency and reduces manufacturing costs.

5. Conclusion

In the past five years, perovskite solar cells have achieved breakthroughs in efficiency, stability (T80 >1500 hours), and industrialization (GW-level production lines), with their high cost-performance ratio and design flexibility posing a serious challenge to the dominance of silicon cells. These advances showcase the tremendous potential of perovskite solar cells in terms of efficiency, stability, and industrialization, providing an important technological foundation for large-scale applications.

Breaking the Efficiency Limit: Achieving 40% efficiency through quantum dot perovskites and triple-layer structures. By introducing quantum dots and multilayer structures, the photovoltaic conversion efficiency of perovskite solar cells can be further improved, achieving higher energy utilization efficiency.

Environmental Friendliness: Development of lead-free materials and the establishment of a closed-loop recycling system. Through the development of lead-free materials and the establishment of a closed-loop recycling system, the environmental friendliness of perovskite solar cells will be significantly enhanced, reducing their environmental impact.

Standardized Production: Establishing IEC testing standards and pushing global production capacity to 100 GW by 2030. By establishing international standards and promoting large-scale production, the market competitiveness of perovskite solar cells will be greatly increased, enabling broader applications.

Perovskite technology is expected to reshape the photovoltaic industry landscape, becoming a core driver for achieving the “dual-carbon” goals, and leading a triple revolution in photovoltaic modules that are highly efficient, low-cost, and widely applicable. Through continuous technological innovation and industrialization, perovskite solar cells are expected to play a significant role in the future energy transition, providing important technological support for achieving sustainable development.

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