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A Comparative Analysis of Characteristics and Development Prospects of Various Perovskite Solar Cell Systems

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Abstract. With the advancement of global carbon neutrality and the upgrading of electrification industries, the replacement of traditional energy by clean energy has become a core industrial trend. As a green renewable power generation technology, solar photovoltaic energy plays a vital role in alleviating energy shortages and reducing carbon emissions. The material characteristics and service performance of different solar cells directly determine the power generation efficiency, operational stability and industrial application potential of photovoltaic devices. This paper systematically reviews the structural characteristics, photoelectric properties, advantages and application limitations of organic-inorganic hybrid, all-inorganic, lead-free and tandem composite perovskite solar cells, and summarizes the applicable scenarios and core technical bottlenecks of various cell systems. The results show that hybrid perovskites exhibit excellent photoelectric conversion efficiency but suffer from poor stability; all-inorganic perovskites possess outstanding high-temperature resistance while being restricted by phase instability; lead-free and tandem composite structures can effectively balance device performance, environmental friendliness and practicality. This study clarifies the technical differences and development challenges of different perovskite solar cells, providing effective references for photovoltaic material modification, device structure optimization and low-cost industrialization, and promoting the technological iteration and large-scale application of high-efficiency, stable and eco-friendly solar cells.

Keywords: solar cells, perovskite materials, photoelectric performance

1. Introduction

With the continuous depletion of fossil energy and the increasingly prominent global carbon neutrality goal, renewable solar energy has become the core alternative to traditional energy sources in the new energy era. Silicon-based solar cells currently dominate the commercial photovoltaic market due to their mature manufacturing technology and reliable operational stability. However, they are restricted by high production energy consumption, rigid device structure and gradually saturated photoelectric conversion efficiency, which limits the further reduction of photovoltaic power generation costs and large-scale popularization [1]. Therefore, developing low-cost, high-

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efficiency and flexible new-generation photovoltaic technologies has become a key research direction in the field of solar energy.

Perovskite solar cells (PSCs) have attracted widespread global attention owing to their excellent photoelectric properties, including high light absorption coefficient, long carrier diffusion length, adjustable band gap and low solution-processed preparation cost. Since the first prototype with a power conversion efficiency (PCE) of 3.8% was reported in 2009, PSCs have achieved a certified efficiency of 27.0% in just over a decade, rapidly catching up with the performance of commercial monocrystalline silicon solar cells [2]. In recent three years, domestic and foreign researches have focused on interface defect passivation, precursor crystallization regulation, and tandem device construction. Advanced interface modification strategies have been proven effective in optimizing carrier transport and reducing film defects, significantly boosting device photovoltaic. Meanwhile, innovative precursor regulation and vacuum processing technologies have greatly improved the photothermal stability of perovskite films under actual solar irradiation. Machine learning has also been widely applied to screen optimal perovskite components and device structures, providing efficient solutions for developing high-stability photovoltaic devices suitable for outdoor high-temperature environments. Additionally, the rapid development of all-perovskite tandem devices and 2D-3D composite perovskite structures further expands the application potential of PSCs in high-efficiency solar power [3]. These breakthroughs in ambient atmospheric preparation, thermal and light stability optimization, and tandem photovoltaic technology effectively promote the industrialization process of PSCs.

Nevertheless, the large-scale commercial application of PSCs still faces prominent bottlenecks. The intrinsic defects of perovskite crystals and the vulnerability of organic components to moisture, high temperature and ultraviolet irradiation will cause irreversible device attenuation, resulting in poor long-term operational stability. In addition, the uncontrollable crystallization process of perovskite films easily produces grain boundaries and micro-defects, which reduces carrier transmission efficiency and restricts the further improvement of device efficiency. Although numerous studies have explored modification strategies to optimize film quality and interface performance, there are still deficiencies in low-cost, simple-operated and universal optimization schemes suitable for industrial photovoltaic production.

Based on the above research background and recent research progress, this paper takes efficient and stable perovskite solar cells as the research object. It systematically summarizes the latest research progress of PSCs in film preparation optimization and interface modification in recent years, analyzes the main failure mechanisms of devices under light and thermal conditions, and explores feasible optimization strategies to improve film quality and suppress defect recombination. The research aims to solve the problems of low efficiency and poor stability of traditional PSCs, provide theoretical support and technical reference for the preparation of high-performance perovskite photovoltaic devices, and lay a foundation for the low-cost and large-scale application of new solar photovoltaic technology.

2. Working principle of solar cells

The core working mechanism of solar cells is the photovoltaic effect, which refers to a semiconductor photoelectric conversion technology that directly converts solar light energy into electrical energy and serves as the fundamental principle of all photovoltaic devices. Traditional solar cells are mainly based on PN junction structures formed by combining P-type and N-type semiconductors. A built-in electric field is spontaneously established at the junction interface,

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providing a driving force for the separation of photogenerated carriers and realizing continuous photoelectric energy conversion.

The complete photoelectric conversion process includes four key stages. First, photon absorption and carrier excitation. When sunlight irradiates the active layer of a semiconductor material, photons with energy higher than the semiconductor band gap are absorbed, exciting electrons from the valence band to the conduction band and generating free photogenerated electron-hole pairs, namely photocarriers. Second, carrier separation. Without an internal electric field, electrons and holes rapidly recombine and fail to produce effective electric energy. The built-in electric field of the PN junction promotes directional migration: electrons move toward the N-type region and holes move toward the P-type region, effectively suppressing carrier recombination. Third, carrier transmission and collection. The separated electrons and holes are transmitted to external circuits through electrodes on both sides of the device, forming a continuous photocurrent in a closed loop. Fourth, electric energy output. When the external circuit is connected to a load, stable electric power output is achieved, completing the overall energy conversion from light to electricity [4].

As a new generation of semiconductor photovoltaic devices, perovskite solar cells follow the basic photovoltaic mechanism while possessing unique optoelectronic advantages. Compared with traditional silicon-based solar cells, perovskite materials exhibit a higher light absorption coefficient and superior carrier migration performance, enabling efficient sunlight absorption with thin film thickness and greatly improving photoelectric conversion efficiency. The overall performance of perovskite solar cells, including efficiency, stability and fill factor, is determined by the entire process of carrier generation, separation, transmission and recombination. Optimizing film quality, regulating interface structure and improving crystallization performance are effective strategies to enhance photovoltaic performance [5].

3. Classification, advantages and disadvantages of perovskite solar cells

According to material composition and structural characteristics, mainstream perovskite solar cells are divided into three categories: organic-inorganic hybrid lead-based perovskites, all-inorganic lead-based perovskites, and lead-free perovskites. In addition, novel high-efficiency photovoltaic systems such as tandem and composite perovskite structures have been rapidly developed. Different types of perovskite devices show distinct differences in photoelectric performance, stability, preparation difficulty and application scenarios, adapting to various solar photovoltaic working conditions.

3.1. Organic-inorganic hybrid lead-based perovskite solar cells

Organic-inorganic hybrid lead-based perovskites are the most mature and high-performance photovoltaic materials at present, with a typical ABX_3 crystal structure. In this structure, the A-site represents organic cations such as formamidine and methylamine, the B-site is lead ion, and the X-site corresponds to halogen ions including chlorine, bromine and iodine. The working principle is consistent with conventional perovskite photovoltaic devices. The hybrid perovskite active layer absorbs solar photons to generate electron-hole pairs, which are subsequently separated and collected through interface transport layers to output electric power. The synergistic effect of organic and inorganic components endows the device with excellent comprehensive optoelectronic properties.

This type of perovskite solar cell possesses prominent advantages. Firstly, it achieves outstanding photoelectric performance with long carrier diffusion length and low recombination rate, delivering

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the highest photoelectric conversion efficiency among all perovskite systems and approaching the efficiency level of commercial silicon-based solar cells. Secondly, the preparation process is simple and low-cost. Low-temperature solution methods such as spin-coating and blade coating can be adopted without high-temperature equipment, which is suitable for large-scale industrial production. Thirdly, the band gap is tunable by adjusting halogen ratios and organic cation components, enabling precise matching with solar spectra and satisfying the preparation requirements of tandem solar cells.

Nevertheless, hybrid lead-based perovskites have obvious application limitations. The organic cations are thermally unstable and tend to volatilize and decompose under high-temperature and continuous illumination, resulting in structural collapse of perovskite films and severe performance attenuation, which restricts their outdoor high-temperature photovoltaic applications [6]. Moreover, organic components are extremely sensitive to moisture and oxygen in the atmosphere, causing gradual film degradation and requiring strict preparation and encapsulation conditions. In addition, the inclusion of toxic lead elements brings potential environmental risks, hindering large-scale commercial promotion.

Given the above characteristics, hybrid perovskite solar cells are mainly applied in laboratory high-efficiency photovoltaic research, tandem device fabrication and indoor low-light photovoltaic systems, while they are not suitable for harsh outdoor large-scale photovoltaic power stations at this stage.

3.2. All-inorganic lead-based perovskite solar cells

All-inorganic lead-based perovskites completely eliminate thermally unstable organic cations and adopt inorganic metal cations such as cesium at the A-site. Typical representatives include $CsPbI_3$ and $CsPbBr_3$ inorganic perovskite materials. The photoelectric conversion mechanism is identical to hybrid perovskites: inorganic perovskite crystals absorb sunlight and excite photogenerated carriers to realize light-to-electricity conversion, fundamentally solving the thermal decomposition problem of organic components.

The most prominent advantage of all-inorganic perovskite devices is their excellent thermal stability. Without volatile organic components, the crystal structure maintains high stability under high-temperature solar irradiation, making it applicable for extreme photovoltaic scenarios such as desert and high-temperature summer environments. Meanwhile, inorganic perovskite films feature high crystallinity and compact microstructure, exhibiting better photostability and longer device service life than hybrid perovskites. Furthermore, modified strategies such as pseudo halogen regulation and interface engineering can further optimize photovoltaic performance and enable low-cost device fabrication under ambient conditions [7].

However, all-inorganic perovskites suffer from poor room-temperature phase stability. Typical $CsPbI_3$ tends to undergo spontaneous phase transition at ambient temperature, transforming from the photoactive cubic phase to the inactive orthorhombic phase, which seriously reduces device efficiency and repeatability [8]. In addition, the existence of lead elements still causes environmental concerns, and uncontrollable crystallization induces numerous micro-defects, limiting further efficiency improvement, which remains a key technical challenge for inorganic perovskite photovoltaics.

Such devices are primarily applied in outdoor high-temperature distributed photovoltaic systems, industrial power supply and extreme-environment solar power generation, showing great potential for high-stability photovoltaic applications under harsh conditions.

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3.3. Lead-free perovskite solar cells

Lead-free perovskite solar cells replace toxic lead with non-toxic metal elements such as tin, bismuth and copper, fundamentally eliminating heavy metal pollution risks and representing a key direction for environmentally friendly photovoltaic industrialization. The device structure and photoelectric conversion mechanism are consistent with traditional perovskite systems, realizing photon absorption and carrier transmission through lead-free active layers to balance environmental friendliness and photovoltaic performance.

The core advantage of lead-free perovskites is environmental safety and non-toxicity, which conforms to the green and low-carbon development trend of the photovoltaic industry and is suitable for building-integrated photovoltaics and residential solar power systems. In addition, some tin-based lead-free perovskites possess narrower band gaps and broader solar spectral absorption ranges, showing outstanding theoretical photoelectric conversion potential.

Currently, lead-free perovskite devices still face significant technical bottlenecks. Lead-free materials generally suffer from poor chemical stability; tin-based perovskites are easily oxidized and degraded, resulting in poor film quality and high grain boundary defect density, which causes severe carrier recombination [9]. Meanwhile, their photoelectric conversion efficiency, carrier mobility and charge transport capability are far inferior to lead-based perovskites, with poor preparation repeatability. At present, lead-free perovskites are still in the stage of fundamental laboratory research with low industrial maturity.

3.4. Novel high-efficiency perovskite solar cells

With the rapid development of photovoltaic technology, innovative high-efficiency perovskite systems have emerged, mainly including perovskite/silicon tandem solar cells, all-perovskite tandem devices and 2D/3D composite perovskite structures, which have become research hotspots in high-efficiency solar photovoltaics. Through structural innovation, interface optimization and precursor engineering regulation, novel devices effectively break the efficiency limit and stability bottleneck of single-junction perovskite solar cells.

Perovskite/silicon tandem solar cells combine the advantages of mature, stable silicon-based photovoltaics and high-absorption, bandgap-tunable perovskite materials. The upper and lower layers realize complementary solar spectral utilization, making full use of full-band sunlight and significantly boosting photoelectric conversion efficiency, exceeding the theoretical limit of single-junction devices. This technology is highly compatible with existing silicon photovoltaic production lines and has great industrialization potential for large-scale centralized photovoltaic power stations [10]. All-perovskite tandem cells adopt wide/narrow bandgap matching strategies to achieve precise spectral utilization, featuring lightweight and flexible characteristics that adapt to building-integrated photovoltaics and portable photovoltaic equipment [11].

Furthermore, emerging technologies including machine learning-assisted optimization, interface defect passivation and precise vacuum fabrication can effectively solve the photothermal attenuation and uneven crystallization problems of traditional perovskite devices, greatly improving outdoor operational stability under drastic temperature changes and intense solar irradiation. Although current high-efficiency perovskite devices still need to solve interface stress matching, long-term operational stability and large-scale preparation consistency problems, their advantages of high efficiency, low cost and multi-functionality make them a core development direction for next-generation solar photovoltaic technology.

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4. Prospect of solar cells

With the steady advancement of the global carbon neutrality goal, solar photovoltaic power has become increasingly important in the clean energy system. As a disruptive new-generation photovoltaic technology, perovskite solar cells possess outstanding optoelectronic performance and low-cost manufacturing advantages, which can effectively compensate for the shortcomings of traditional silicon-based solar cells. In the future, continuous breakthroughs in technological innovation, cost reduction and industrial application will further promote the comprehensive upgrading of the photovoltaic industry.

In terms of technological innovation, insufficient long-term stability and obvious operational attenuation are the core bottlenecks restricting the industrialization of perovskite solar cells. Machine learning-assisted component screening and interface modification strategies can precisely optimize the microstructure of perovskite films and greatly improve the high-temperature resistance of devices, enabling stable and efficient operation under severe extreme working conditions. In the iterative development of tandem devices, precise regulation of colloidal precursor nucleation kinetics effectively suppresses phase segregation of sub-cells. At present, the certified efficiency of all-perovskite tandem solar cells far exceeds the efficiency limit of single-junction perovskite devices. Furthermore, optimizing the attenuation mechanism of wide-bandgap perovskites under rapid thermal cycling and alternating temperature conditions can substantially enhance the long-term operational stability of outdoor photovoltaic devices.

In terms of cost and fabrication, conventional perovskite devices require strict anhydrous and oxygen-free manufacturing environments, which greatly increases mass production costs. Relevant studies have proven that pseudo halogen regulation technology enables the fabrication of high-performance wide-bandgap perovskite devices under ambient atmospheric conditions, which simplifies the preparation process and reduces equipment investment without sacrificing photovoltaic performance. Compared with the high-temperature manufacturing process of silicon-based cells, the low-temperature solution processing of perovskite materials significantly cuts down manufacturing energy consumption, showing great potential for low-cost mass production and promoting the comprehensive affordability of photovoltaic power generation.

In terms of industrial application, different types of perovskite solar cells exhibit distinct application advantages. Benefiting from the organic-component-free structure, all-inorganic lead-based perovskites possess excellent thermal stability and thermal aging resistance, making them suitable for harsh outdoor environments with high temperature and drastic temperature changes, and they can effectively resist structural damage caused by rapid thermal cycling. Optimized all-perovskite tandem devices can retain most of their initial efficiency after long-term continuous illumination at the maximum power point, demonstrating greatly improved operational durability. With the continuous maturity of large-area fabrication and encapsulation technology, perovskite solar cells can be widely applied in building-integrated photovoltaics, distributed power generation and portable photovoltaic equipment, realizing large-scale industrial promotion in the future.

5. Conclusion

This paper systematically investigates the effects of different perovskite materials on the photoelectric performance and practical value of solar cells. The results show that the current perovskite photovoltaic system mainly consists of organic-inorganic hybrid lead-based perovskites, all-inorganic lead-based perovskites, lead-free perovskites and novel composite tandem perovskite structures. Organic-inorganic hybrid lead-based perovskites remain the most widely adopted

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materials for laboratory high-efficiency photovoltaic research due to their simple fabrication, excellent carrier transport capability and superior photoelectric conversion efficiency. However, they are limited by poor thermal stability, weak moisture and oxygen resistance, and lead-containing environmental risks. All-inorganic lead-based perovskites exhibit prominent high-temperature stability and are suitable for extreme outdoor photovoltaic scenarios, whereas their application is restricted by room-temperature phase instability and abundant crystalline defects. As emerging photovoltaic systems, lead-free perovskites and tandem composite structures serve as effective transitional and upgraded solutions, achieving a favorable balance in performance improvement, environmental safety and industrialization feasibility.

Therefore, the future technological upgrading of perovskite solar cells should focus on efficiency improvement, stability enhancement and low-cost fabrication. Advanced strategies including precursor colloidal regulation, machine learning-assisted optimization and ambient-air pseudo halogen modification can effectively improve the photoelectric performance and environmental tolerance of devices and solve common industrial problems such as thermal cycling attenuation and harsh fabrication requirements]. The collaborative innovation of scientific research institutions and the photovoltaic industry will further promote the industrialization of high-efficiency tandem devices and thermally stable inorganic perovskite devices, providing important technical support for the large-scale, low-cost and long-term stable commercial application of next-generation perovskite photovoltaic technology.

References

[1] Liu, T., Chen, Y., Zhang, T., et al. (2026). Tailoring colloidal precursor chemistry for tunable nucleation kinetics in all-perovskite tandem solar cells. *Joule, 10*(4), 102381.

[2] Ding, Y., Zhang, Z., Li, M., et al. (2026). Unlocking 27.3% perovskite photovoltaics by interface-locked dual-molecule contact. *Science Advances, 12*(7), aeg1456.

[3] Jiang, X. Z., Wegener, S. A., & Li, Y. X. (2026). Insights into the operational stability of wide-bandgap perovskite and tandem solar cells under rapid thermal cycling. *Nature Communications, 17*(1), 1245.

[4] Mota, F., Silva, J., & Costa, A. (2026). Photons as working body for photovoltaic devices: Conversion of photon to electron from a simplified perspective. *Advanced Theory and Simulations, 9*(1), 2502034.

[5] Li, F., Wang, H., & Zhao, J. (2025). Machine learning assisted synergistic optimization of anti-reflection film structural design and interface modification for efficient and stable perovskite solar cells. *Acta Physica Sinica, 74*(18), 188801.

[6] Guo, J., Ma, Q., Madsen, M., et al. (2026). AI-guided design of efficient perovskite solar cells operationally stable at 100 °C. *Science, 392*(6772), 724–728.

[7] Tian, X. B., Yu, P. R., & Zhang, Z. H. (2026). Pseudohalogen modulation technology for air-fabricated high-efficiency inverted wide-bandgap inorganic perovskite photovoltaic devices. *Acta Materiae Compositae Sinica, 43*(7), 4242–4249.

[8] Liu, C., Ma, X., & Zhao, H. (2024). Origins of room-temperature phase transition and intrinsic defects in cesium lead halide inorganic perovskites. *Journal of Materials Chemistry A, 12*(27), 16214–16224.

[9] Wu, Y., Yang, S., Li, E., Liu, Y., Yuan, F., Wen, J., Hua, L., Wang, W., Yang, Y., Lei, Y., Chu, J., & Li, W. (2025). Low-dimensional templates and delayed crystallization for high-quality tin-based perovskite films and high-performance transistors. *Nature Communications, 16*(1), 9505.

[10] Sun, X., Wang, L., Zhang, H., et al. (2026). Impact of ultrathin electron-selective contacts on perovskite–silicon tandem solar cells. *ACS Energy Letters, 11*(4), 1562–1569.

[11] Gharibzadeh, S., Hu, H., Diercks, A., Feeney, T., Richards, B. S., Abzieher, T., & Paetzold, U. W. (2026). Translucent perovskite photovoltaics for building integration. *Progress in Photovoltaics, 34*(2), 211–228.