Characteristics of Emerging Perovskite Solar Cell Technology

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Abstract. With the continuous growth of energy demand and the increasingly prominent environmental problems of fossil energy, the development of clean and renewable energy has become an important direction of energy structure transformation. Perovskite solar cells have the advantages of high light absorption coefficient, low temperature preparation and adjustable band gap. However, problems such as insufficient long-term stability, environmental risk of lead, and attenuation of large-area preparation performance still limit the industrialization process. This paper focuses on three types of perovskite solar cell systems: organic-inorganic hybrid lead-based, tin-lead hybrid and all-inorganic lead-based. The crystal structure, photoelectric properties, preparation process and application characteristics are reviewed, and the main optimization strategies such as material regulation, interface passivation, lead-free and tandem devices are analyzed. At the same time, the stability, large-scale preparation and environmental safety problems faced by the current perovskite photovoltaic technology are summarized. The research shows that different perovskite systems have their own characteristics in photoelectric performance, stability and application direction. Composite material design, component optimization and high barrier packaging technology are important ways to improve device performance and life. This paper can provide reference for the subsequent technology optimization and industrialization development of perovskite solar cells.

Keywords: Perovskite solar cells, photoelectric conversion efficiency, stability, lead-free.

1. Introduction

In recent years, global industrialization has continued to advance in depth, and the energy demand of the whole society has shown an explosive growth trend. Traditional fossil energy sources such as coal, oil and natural gas have long dominated the energy supply system. On the one hand, these resources are facing supply constraints such as the decline of resource reserves year by year and the continuous increase of mining, storage and transportation costs. On the other hand, the burning of a large number of fossil fuels has led to global ecological problems such as excessive greenhouse gas emissions, increased air pollution, and frequent extreme climate events [1]. Therefore, human beings urgently need to explore greener energy systems to ensure sustainable development. As the most abundant renewable energy with the most balanced spatial distribution, solar energy has natural advantages such as zero fuel consumption, strong regional adaptability, and local distributed development. Therefore, solar photovoltaic cell technology has become a key frontier research direction in the cross field of global material science and energy engineering.

Compared with mainstream sustainable power generation forms such as thermal power, hydropower, and wind power, photovoltaic power generation has irreplaceable environmental friendliness. There is no release of harmful pollutants such as carbon dioxide, sulfide and nitrogen oxides in the whole process of photovoltaic power generation, which can avoid the ecological damage problems such as haze, acid rain and greenhouse effect caused by fossil energy combustion from the source. In addition, photovoltaic power stations can be arranged in low-efficiency land such as desert gobi, idle building roofs, tidal flat salt fields, etc., and will not compete with grain production for cultivated land resources. Compound development models such as salt-light complementarity and agricultural-light complementarity can better realize the three-dimensional and efficient use of land resources. At present, the industrialization technology of mainstream crystalline silicon solar cells has matured, and the photoelectric conversion efficiency of mass production is constantly approaching the theoretical limit. However, the core processes such as purification and silicon wafer

cutting have high energy consumption, and the preparation process is lengthy and complicated. The manufacturing cost of the crystalline silicon laminated efficiency scheme is high, and it is difficult to quickly reduce the cost of photovoltaic power generation. The industry urgently needs a new generation of high-performance and low-cost photovoltaic technology to complete industrial innovation.

Perovskite solar cells have achieved rapid development since their inception in 2009. Its laboratory-certified photoelectric conversion efficiency has increased from an initial 3.8% to 27.3%[2]. In the course of more than ten years of development, it has achieved an efficiency level close to that of traditional crystalline silicon photovoltaic technology accumulated over decades. Perovskite materials are considered to be an important research direction of the third-generation photovoltaic technology due to their high light absorption coefficient, low temperature preparation advantages and adjustable band gap. However, these batteries still face many challenges in practical applications, including insufficient long-term stability, environmental impact of lead, and performance degradation of large-area devices [3]. Under the background of this era, new perovskite solar cells have emerged as the core representative technology of the third-generation photovoltaic cells. Perovskite light absorbing materials have excellent photoelectric properties such as high light absorption coefficient, long carrier diffusion length and adjustable band gap. At the same time, thin film preparation can be realized by low temperature solution processing, spin coating and printing coating. Compared with the complex high-temperature preparation process of traditional crystalline silicon batteries, perovskite technology has potential advantages in manufacturing energy consumption and process simplification, and shows the possibility of further reducing production costs and achieving large-scale applications [4]. At the same time, this type of battery can be used to prepare lightweight and flexible thin film devices, which are suitable for multiple application scenarios such as building photovoltaic integration, flexible wearable electronics, aerospace equipment, and deep space exploration equipment. If a laminated photovoltaic device is constructed with a crystalline silicon cell, the theoretical photoelectric conversion efficiency can break through 45%, opening up a new direction for the photovoltaic efficiency to break through the existing bottleneck. Many countries in the world have incorporated perovskite photovoltaic technology into the national key development plan of energy science and technology. China has also specially deployed high-efficiency perovskite battery industrialization technology research tasks. A number of G-watt mass production lines are planned to be completed and put into operation in 2026, marking that the technology is rapidly moving from laboratory basic research to commercial landing stage, and has important strategic value in the process of global energy low-carbon transformation and carbon neutrality target landing [5].

Although the new perovskite battery has broad application prospects, there are still many key technical shortcomings in this system at this stage: poor long-term working stability of the device, potential environmental hazards of lead-based active materials, significant degradation of photoelectric performance of large-area modules, and low conversion efficiency of lead-free perovskite systems. Many problems seriously limit its large-scale application. Researchers at home and abroad have carried out a large number of systematic studies on the precise control of components, interface passivation modification, optimization of packaging protection process, development of new lead-free perovskite materials, and design of laminated integrated devices, and accumulated rich phased research results. However, the existing review literature is mostly limited to the summary of a single material system or a single preparation process, and lacks a systematic review of the research progress in the whole field of perovskite batteries in recent years. It is impossible to fully clarify the technological evolution context, existing core technology bottlenecks and subsequent optimization and improvement ideas.

This paper focuses on the macro-strategic needs of sustainable development of energy and environment, combined with the industry background of the iterative upgrading of the global photovoltaic industry, summarizes the important breakthroughs of new perovskite batteries in the direction of material modification, device structure design, preparation process optimization, stability

enhancement, lead-free green transformation, laminated composite device research and development, summarizes the common defects of the current technology, compares and analyzes the advantages and disadvantages of various optimization schemes and applicable scenarios, and prospects the development trend of industrialization, greening, high efficiency and high stability.

2. The Working Principle of Solar Cells

The sunlight first passes through the transparent conductive glass electrode and shines on the perovskite light absorbing layer in the middle. This material has a particularly strong light absorption ability, and a layer of several hundred nanometers thick can absorb most of the visible light. Photons play up, as long as the energy is up to standard, the electrons in the valence band of the material can be excited to the conduction band, while leaving a positively charged hole, that is, a pair of electron hole pairs. Unlike many organic photovoltaic materials, the electron and hole binding force in perovskite is very weak, and it can be automatically separated into free-moving charges without additional energy at room temperature, saving loss [6]. Then it is driven by the energy level difference of each layer of material: the negatively charged electrons run to the electron transport layer with lower energy level, and finally converge to the transparent electrode at the bottom; the positively charged holes go to the hole transport layer with higher energy levels, and finally to the top metal back electrode. These two sets of charges are connected through an external circuit. The electrons flow out from the negative electrode, circle the circuit and then return to the positive electrode, forming a continuous current that can be used directly [7].

The perovskite light-absorbing layer material has a visible light absorption coefficient much higher than that of crystalline silicon. Only a 200-500nm film can completely capture photons in the visible light band, greatly reducing the amount of active materials. Unlike organic photovoltaic materials, perovskite exciton binding energy is extremely low, and electrons and holes can spontaneously dissociate into free carriers at room temperature, without additional dissociation energy, significantly reducing charge recombination loss. When the device is working, the sunlight reaches the perovskite layer through the transparent conductive substrate, the photogenerated electrons converge to the bottom electrode along the electron transport layer with lower energy level, and the holes migrate to the metal back electrode along the hole transport layer with higher energy level. The charge is circulated through the external circuit to form a stable output current. At the same time, the band gap of the material can be continuously regulated by halogen components, which is suitable for multiple application scenarios such as laminated batteries, indoor photovoltaics, photodetectors, etc [8]. The exciton binding energy of hybrid perovskite is extremely low, and free carriers can be spontaneously dissociated at room temperature [9].

Perovskite materials are generally composed of methylamine lead iodide, methylamine cesium lead iodide, etc., which have the characteristics of strong light absorption and long carrier diffusion length [10]. Among them, PN junction solar cells have certain representativeness. The PN junction is formed by p-type and n-type semiconductor contacts, and the carrier diffusion on both sides of the contact surface forms a depletion layer and a stable built-in electric field, which is the core structure of the photovoltaic effect [11]. When there is no light, the diffusion motion and the built-in electric field drift motion reach a dynamic balance; when the sunlight irradiates the PN junction region, the photon excitation generates electron-hole pairs, and the built-in electric field quickly separates the positive and negative carriers. The electrons migrate to the n-region and the holes migrate to the p-region. The external circuit can output the photogenerated current, and the open-circuit photogenerated voltage is formed when the circuit is disconnected, and the photoelectric conversion is completely realized. This physical model is the theoretical basis of most thin-film photovoltaic devices such as crystalline silicon and perovskite [12]. As the core structure of photovoltaic devices, the photoelectric conversion limit of PN junction can be quantitatively described by Shockley-Queisser fine balance theory, which lays a calculation framework for the upper limit of efficiency of single-junction solar cells and is suitable for the performance analysis of most thin-film photovoltaic

devices such as crystalline silicon and perovskite. Fig.1 shows the basic principle and structure of PN junction solar cells.

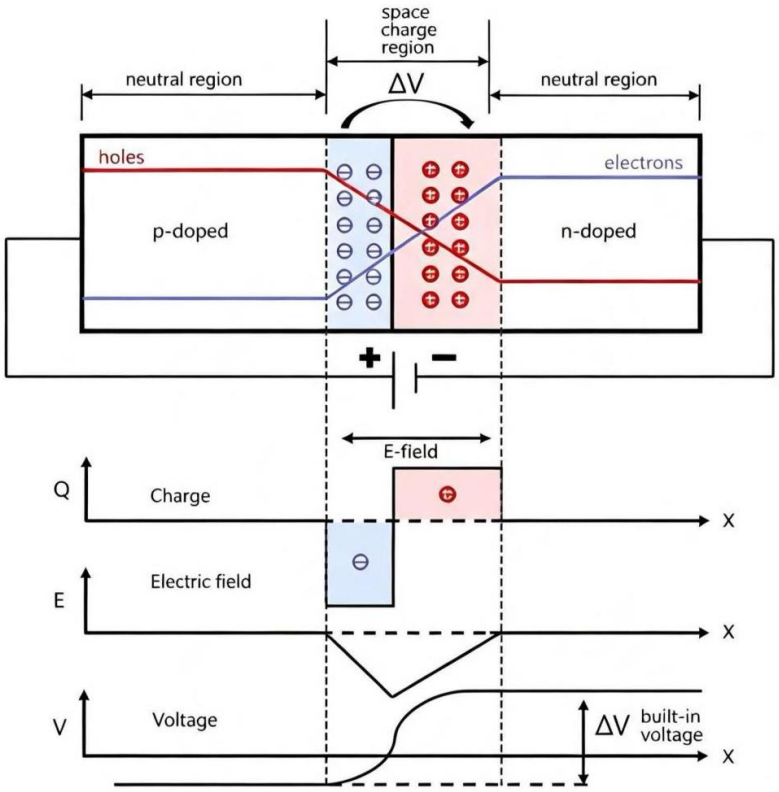


Fig. 1 The working principle of PN junction solar cells [10]

3. Advantages and Disadvantages of Perovskite Batteries

3.1. Organic-inorganic Hybrid Lead-based Perovskite Battery

Organic-inorganic hybrid lead-based perovskite solar cell is a kind of thin film photovoltaic device with ABX_3 perovskite crystal structure of organic-inorganic hybrid lead halide compound as the core light absorption layer, which belongs to the third-generation solar cell category. Among them, the A site is a monovalent organic cation (typical methylamine cation MA^+, formamidine cation FA^+); b site is divalent lead ion (Pb^{2+}); the X-site is a monovalent halogen anion (I^-,Br^-,Cl^- or their mixed components). Tin-lead hybrid perovskite extends the absorption edge to the near-infrared band of 1000 nm by partially replacing Pb^{2+} with Sn^{2+}, which is suitable for all-perovskite tandem batteries and can achieve carrier life of more than 1 μs. However, Sn^{2+} is easily oxidized to form deep-level defects, which greatly shortens the service life of the device [13]. The material has both the high carrier mobility of inorganic components and the film-forming flexibility and solution processing characteristics of organic components.

As a new generation of photovoltaic light absorbing layer materials, perovskite materials have many outstanding performance advantages. In terms of optical properties, its absorption coefficient in the visible light band is extremely high, and only a film of 200-500 nm thick can be used to fully capture visible light. The thickness is much lower than that of traditional micron-sized crystalline silicon wafers, which can greatly reduce the amount of active raw materials. At the same time, the band gap of perovskite can be flexibly adjusted by adjusting the proportion of halogen components, which can be well matched with the solar spectrum, laying a thermodynamic foundation for efficient photoelectric conversion. In terms of carrier transport performance, the diffusion length of electrons and holes in perovskite can reach the order of microns, and the energy loss caused by charge recombination is low. Thanks to this characteristic, the laboratory photoelectric conversion efficiency of single-junction perovskite cells has increased rapidly, and the highest value has exceeded 26%. At

the level of preparation process, perovskite films can be prepared by various low-temperature solution methods such as spin coating, scraping coating and printing, without high-temperature sintering process, which not only reduces production energy consumption and manufacturing cost, but also adapts to flexible substrates, showing great potential for large-scale mass production. In addition, perovskite solar cells have excellent weak light response performance and unique adaptability in subdivision application scenarios such as indoor photovoltaics and building transparent photovoltaics.

However, the commercialization of perovskite batteries still faces several core bottlenecks. The first is the risk of environment and recovery. The mainstream perovskite system contains heavy metal lead. If the waste devices are not properly disposed of, the leakage of lead will cause heavy metal pollution in the water and soil environment, which will push up the cost of environmental protection compliance and end treatment. The lead recovery process of waste batteries is complicated and has not yet formed a mature industrialization path. The second is the lack of long-term stability. The organic cations in perovskite crystals (such as methylamine MA, formamidine FA) have poor thermal stability, and are prone to crystal structure decomposition in outdoor environments with high temperature and high humidity, resulting in rapid degradation of device performance. The outdoor service life is far less than that of mature silicon-based photovoltaic devices. Finally, the halogen ions inside the perovskite are easy to migrate under the action of the external electric field, which will induce the current-voltage hysteresis effect, further reduce the output performance stability of the device, and adversely affect the power output reliability in practical applications.

In the subdivision field where the spectral response has special requirements, the long-wave absorption characteristics of tin-lead hybrid perovskites have unique advantages. The light absorption edge of the system can be extended to the near-infrared region above 1000nm, which makes up for the shortcomings of the pure lead system in the utilization of long-wave photons. In special scenarios such as concentrating photovoltaic and near-infrared light energy acquisition, the photon capture efficiency per unit area can be effectively improved. In low-light outdoor environments such as cloudy days and dawn and dusk, its ability to utilize long-wave scattered light can also maintain more stable power output, which is suitable for working conditions with low light and high proportion of long-wave. In addition, relying on the continuously adjustable band gap and high carrier mobility, tin-lead hybrid perovskite can also be used to construct optoelectronic devices such as wide-spectrum photodetectors and circularly polarized light detection units, which have clear research and application prospects in the fields of optical communication, environmental monitoring and biological imaging.

From the perspective of environmental adaptation and civil landing, the low-lead characteristics of tin partially replacing lead expand the application boundary of perovskite batteries in close-range civil scenarios. Compared with the pure lead system, the lead content of the tin-lead hybrid perovskite active layer is significantly reduced, which alleviates the risk of heavy metal leakage and environmental compliance pressure of waste devices to a certain extent. It is more suitable for building photovoltaic integration, wearable energy equipment, indoor off-grid power supply and other scenes that are highly overlapped with human activities. At the same time, the material system retains the process advantages of low-temperature solution processing, and can be adapted to large-area preparation technologies such as scraping and printing and flexible substrates. It can be made into lightweight and translucent photovoltaic modules to meet the differentiated power supply requirements of building curtain walls, portable consumer electronics and other scenarios.

As far as the current technical stage is concerned, due to the easy oxidation of divalent tin and the lack of long-term operation stability of the device, there are still bottlenecks in the outdoor large-scale application of tin-lead hybrid perovskite. Most of the scenarios are still in the stage of laboratory research and development and small-scale demonstration.

3.2. All-inorganic Lead-based Perovskite Battery

All-inorganic lead-based perovskite solar cells are an important branch of technology developed for the bottleneck of thermal stability of organic-inorganic hybrid systems in the field of perovskite

photovoltaics. The core light absorption layer is an all-inorganic lead halide compound with ABX-type perovskite crystal structure, which completely eliminates volatile organic cation components such as methylamine (MA^+) and formamidine (FA^+) in the traditional system. In the lattice of this kind of material, the A-site is a monovalent inorganic cation. The current research system takes cesium ion (Cs^+) as the absolute mainstream, and some lattice control schemes will introduce rubidium ion (Rb^+) for component adaptation. The B-site is a divalent lead ion (Pb^2), which forms a crystal skeleton through the common top connection of the lead halide octahedron; the X-site is a monovalent halogen anion, covering iodine (I^-), bromine (Br^-), chlorine (Cl^-) and their mixed systems, and the continuous wide regulation of the band gap can be achieved by adjusting the halogen ratio. From the perspective of the intrinsic properties of the material, the all-inorganic lattice eliminates the failure path of decomposition and volatilization of organic components, and the thermal stability and UV radiation resistance are significantly improved compared with the hybrid system. Typical research systems include $CsPbI_3$, $CsPbBr_3$ and halogen mixed polycrystalline cesium lead halide films.

Compared with organic-inorganic hybrid perovskites, the core advantage of all-inorganic lead-based perovskites is the intrinsic improvement of the stability dimension. Due to the complete abandonment of volatile organic cations such as methylamine and formamidine, the thermal tolerance of the lattice structure is significantly enhanced. The conventional system can withstand continuous thermal effects above 100°C. Some bromine-iodine blends can even maintain phase stability for a long time at a high temperature of 250 °C, which fundamentally eliminates the device failure path caused by the volatilization of organic components in the hybrid system, and has natural adaptability to outdoor photovoltaic scenarios in high temperature regions. At the photoelectric performance level, this kind of material also retains the excellent endowment of the perovskite family: the carrier migration rate is at a high level, the diffusion length can reach the micron level, and the charge recombination loss is at a low level; at the same time, the wide adjustment of the band gap can be realized by adjusting the halogen composition, covering the wide band gap range of 1.7 ~ 2.3 eV. Combined with the tin-lead alloying method, it can be further extended to the narrow band gap range, which can flexibly adapt to the band gap requirements of the top and bottom cells in the tandem cell, and provide a material basis for the construction of efficient tandem photovoltaic devices. In addition, the photochemical inertia of the inorganic component also gives it better light aging resistance. Compared with the hybrid perovskite, its crystal decomposition rate in the ultraviolet irradiation environment is significantly slowed down, and the performance degradation under long-term illumination is effectively alleviated. The all-inorganic $CsPbI_3$ perovskite eliminates volatile organic cations, and its thermal stability is significantly better than that of the hybrid system. However, the active black perovskite phase is easy to spontaneously transform into the lightless active δ phase at room temperature, and the irreversible phase transition can be inhibited by interface passivation and halogen mixing [14].

However, all-inorganic lead-based perovskites have not solved all bottlenecks, but have derived new problems due to all-inorganic lattice characteristics. The most prominent is the defect of phase stability at room temperature. Taking the typical $CsPbI_3$ system as an example, the black perovskite phase with photoelectric activity belongs to the thermodynamic metastable state at room temperature, which will spontaneously transform to the yellow orthorhombic δ phase with non-perovskite structure. This phase has almost no photoelectric conversion ability, and the transformation process is accompanied by the irreversible collapse of device efficiency. This intrinsic thermodynamic characteristic has become the biggest obstacle to the application of pure iodine-based all-inorganic perovskite [15]. At the level of preparation process, the solubility of inorganic cesium salt precursors in common organic solvents is limited, and the crystallization process is difficult to control when the solution method is used to form a film, which is very easy to produce structural defects such as pinholes and grain boundaries. When the preparation scale is enlarged from a small area in the laboratory to a large area component, the non-uniformity of the drying rate and nucleation environment around the substrate will be enlarged, and the uniformity of the crystal quality and thickness of the film is difficult to guarantee, which directly leads to a significant decline in the

efficiency of large-area devices. Finally, the old problems of environmental and water vapor stability have not been solved: the material system still uses heavy metal lead as the core component, the lead leakage risk of waste devices is the same as that of hybrid systems, and the cost of environmental protection and lead recovery in the whole life cycle is high; at the same time, pure iodine cesium lead perovskite is still highly sensitive to water vapor. Water molecules will directly destroy its crystal structure and accelerate phase transition. The moisture resistance has not been substantially improved due to inorganicization, and it still needs to rely on high-cost packaging protection. As far as the current technological maturity is concerned, due to the bottleneck constraints such as room temperature phase transition and large-area film-forming defects, all-inorganic lead-based perovskite does not have the conditions to replace crystalline silicon batteries for large-scale ground power station applications. Its commercial landing will take the lead from the subdivision scenarios with high added value and strict stability requirements, and gradually expand the application boundary with the iteration of material engineering and preparation process.

3.3. Summary

The organic-inorganic hybrid lead-based perovskite has the best comprehensive photoelectric performance and the most mature solution processing technology, which is the current efficiency record-keeping system. However, the MA / FA organic cation is easy to decompose in hot and humid environment, and the long-term outdoor stability of the device is insufficient, and the lead component has the risk of soil and water pollution. The tin-lead hybrid system partially replaces lead by Sn^{2+}, broadens the spectral response to the near-infrared region, and adapts to the tandem battery and low-light power generation scenarios. The reduction of lead content alleviates the pressure of environmental protection, but Sn^{2+} is easily oxidized to form deep-level defects, which greatly shortens the service life of the device. All-inorganic cesium lead perovskite completely removes volatile organic cations, and its thermal stability and UV irradiation resistance are significantly improved, which is suitable for high temperature special working conditions. However, its active black perovskite phase is thermodynamically unstable at room temperature and spontaneously transforms into a light-free active δ phase. In addition, the solubility of inorganic precursors is poor, and the uniformity of large-area films is difficult to control. The three types of systems have their own advantages and disadvantages. It is necessary to optimize the material composition and packaging process according to the application scenarios [16].

4. The Prospect of Solar Cells

Crystalline silicon solar cell is the core application product of large-scale ground photovoltaic power station, industrial and commercial centralized photovoltaic base and household distributed photovoltaic system. With the advantages of mature technology, simple operation and maintenance, high stability and long service life, it is suitable for large-scale, long-period and fixed photovoltaic power generation scenarios. After decades of industrial upgrading, the preparation process of crystalline silicon cells has been continuously optimized, the mass production cost has been greatly reduced, and the photoelectric conversion efficiency has been steadily improved. It can meet the large-scale power generation demand of large-scale wind-solar-storage integration projects, and is the main photovoltaic equipment for the current global energy low-carbon transformation. In large-area idle areas such as deserts, Gobi, and mountains, crystalline silicon photovoltaic power stations can achieve centralized energy development, cooperate with energy storage systems to build a stable new energy power supply system, effectively replace traditional fossil energy power generation, and reduce regional carbon emissions. At the same time, crystalline silicon cells are suitable for composite power generation scenarios such as agricultural photovoltaics and complementary fishing and light. While ensuring agricultural and fishery production, photovoltaic power generation is realized, which greatly improves the utilization rate of land resources and has both economic and ecological benefits. However, its own brittleness, high weight, and inability to bend flexibly make it difficult to adapt to

lightweight, curved, and portable special application scenarios, and the application range is obviously limited. In the future, the development of perovskite photovoltaic technology will mainly focus on key directions such as high conversion efficiency, long-term stable operation, lead-free greening and large-scale manufacturing. For the optimization of material system, the effects of crystal structure change, ion migration and carrier loss on device performance can be reduced by means of A/B/X-site multi-element synergistic regulation, low-dimensional perovskite protective layer construction and interface defect regulation, so as to achieve the synergistic improvement of photoelectric conversion efficiency and service life. In terms of preparation process, future research will further promote the development of continuous solution processing technologies such as scraping and roll-to-roll printing, and combine the precise control of crystallization process to improve the quality of large-area film preparation and reduce the performance difference between laboratory small-size devices and actual large-scale components. Aiming at the demand of environment-friendly development, lead-free perovskite material system will become an important research direction. The performance optimization of alternative materials such as tin-based and bismuth-based and the improvement of lead recovery and utilization technology will help reduce the environmental impact of the whole life cycle of the device. The risk of heavy metal pollution in lead-based perovskite solar cells is the core environmental bottleneck restricting its commercialization. Lead-free and low toxicity have become the inevitable development direction of perovskite photovoltaic technology. At present, the industry focuses on the research and development of tin-based, bismuth-based and antimony-based lead-free perovskite systems. Through component regulation and process optimization, the photoelectric efficiency and stability of lead-free devices are improved to replace traditional lead-based perovskite materials. At the same time, in view of the existing lead-based perovskite devices, the complete set of lead recovery and harmless treatment technology has been gradually improved, and the green development system of the whole life cycle has been constructed, taking into account the technical performance and environmental safety, so as to promote the sustainable development of perovskite photovoltaic industry. In terms of industrial applications, silicon / perovskite tandem solar cell technology will become an important breakthrough direction to improve photovoltaic conversion efficiency. By further improving the structure of tandem devices, it is expected to break through the theoretical efficiency limit of 45%. At the same time, the development of new packaging materials with high barrier properties and low manufacturing costs will further improve the practical application reliability of perovskite modules and promote their application in ground photovoltaic power stations, building integrated photovoltaics, aerospace and other fields.

In general, the industrialization process of perovskite photovoltaic in the future not only depends on the continuous innovation of material system and manufacturing process, but also needs the cooperation of industry, university and research. Combined with the development of life cycle environmental assessment and low-cost packaging technology, it provides important support for the commercial application of perovskite solar cells.

5. Conclusion

Focusing on the development needs of photovoltaic technology under the background of low-carbon transformation of new energy, this paper systematically analyzes the structural characteristics, photoelectric conversion mechanism, preparation process and performance of crystalline silicon solar cells and three types of perovskite solar cells: organic-inorganic hybrid lead-based, tin-lead hybrid and all-inorganic lead-based. The advantages, limitations and future development directions of the two types of photovoltaic technologies are compared.

Studies have shown that crystalline silicon solar cells are still the mainstream technology in the field of large-scale photovoltaic power generation due to their mature preparation process, high stability and low operation and maintenance costs. However, limited by the characteristics of silicon materials, the energy consumption of high-purity silicon preparation and the limited space for efficiency improvement, it faces certain challenges to further reduce costs and increase efficiency. In

contrast, perovskite solar cells have the advantages of high light absorption coefficient, low temperature preparation, and adjustable band gap. In recent years, the photoelectric conversion efficiency has been rapidly improved, showing great industrialization potential. Among them, the organic-inorganic hybrid lead-based system has outstanding comprehensive performance, but the stability and lead environmental risk still need to be improved; the tin-lead hybrid system has the advantage of expanding the spectral response range, but the tin ion oxidation problem affects the device life. The all-inorganic lead-based system has good thermal stability, but there are still problems such as phase transition and difficulty in large-area preparation. From the perspective of application, crystalline silicon batteries will continue to play a leading role in traditional scenarios such as large-scale ground power stations. Perovskite batteries are expected to expand in the fields of building photovoltaics, flexible devices and special energy supply due to their lightweight and adjustable performance. In the future, the stability and commercial application of perovskite batteries can be further improved through the development of materials optimization, interface regulation, large-scale preparation and high-performance packaging. Crystalline silicon and perovskite photovoltaic are not a simple alternative relationship. They have synergistic development potential in the direction of laminated technology, and jointly promote the evolution of photovoltaic industry to high efficiency, low cost and sustainable direction.

References

[1] Peng Bi. Perovskite solar cells: rapid development and future prospects. Physics, 2025, 54(8): 529-538.

[2] Anonymous. National Renewable Energy Laboratory. NASA Tech Briefs, 2018, 42(9): 4.

[3] Yuan Han, Chen Xi, Liang Ben, et al. Research progress of passivation layer technology for crystalline silicon solar cells. Acta Physica Sinica, 2025, 74(4): 047801.

[4] Li Zan, Klent Tan, Kim Dan, et al. Scalable fabrication of perovskite solar cells based on screen-printed thin films. Nature, 2022, 611: 728-733.

[5] Xin Fan. Study on administrating science and technology of the government. Studies In Science of Science, 2002, 20(4): 373-376.

[6] Fang Zhao. Interface engineering and lead-free research of all-inorganic perovskite solar cells. Hefei: University of Science and Technology of China, 2020.

[7] Di Cao, Li Wang, Chen Ju, et al. Research on BaFx electron-selective contact for crystalline silicon solar cells. Acta Energiae Solaris Sinica, 2025, 46(6): 245-250.

[8] Huang Zhao, Chen Ni. Calculation of limiting efficiency of heterojunction solar cells based on Shockley-Queisser theory. Acta Physica Sinica, 2025, 74(2): 028801.

[9] Shou Wang, Qun Hao. Detailed balance limit of efficiency of p-n junction solar cells. Journal of Applied Physics, 1961, 32(3): 510-519.

[10] Ding Yi. Characteristics of titanium carbide electron-selective contact materials and their applications in crystalline silicon solar cells. Baoding: Hebei University, 2023.

[11] Wang Cao, Zhang Xi, Zhang Xiao, et al. Theoretical analysis of the performance of organic-inorganic hybrid $CH_3NH_3PbI_3$ perovskite solar cells. Acta Energiae Solaris Sinica, 2026, 47(4): 729-736.

[12] Tong Jie, Song Zhao, Kim Di, et al. Carrier lifetimes of Sn-Pb perovskites enable efficient all-perovskite tandem solar cells. Science, 2019, 364(6439): 475-479.

[13] Zhao Xan, Liu Tan, Ban Qian, et al. Accelerated aging of all-inorganic, interface-stabilized perovskite solar cells. Science, 2022, 377(6603): 307-310.

[14] Zhu Man, Li Jan. Research progress on large-area organic-inorganic hybrid perovskite films and their photovoltaic applications. Materials Reports, 2024, 38.

[15] Wen Yi, Zhao Tian, Wang Xian, et al. An entropy-regulating molecular lock stabilizes formamidine lead halide perovskite. Science, 2026, 392(6778): 1342-1348.

[16] Yuan Chao, Chen Man, Wang Dian, et al. Redox shuttle-stabilized tin-lead perovskites for all-perovskite tandem solar cells. ACS Energy Letters, 2025, 10(12): 4749-4757.