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# Interface Physical Regulation and Performance Optimization of Solid-State Electrolytes and Perovskite Photovoltaic Devices

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**Abstract:** Facing the industrial demands of the "Dual Carbon" strategy and the development of a new generation of optoelectronic energy storage devices, all-solid-state lithium batteries (ASSLBs) and perovskite solar cells (PSCs) have emerged as international research frontiers in the field of advanced new energy materials and devices. Excessively high interfacial impedance, severe non-radiative recombination of defects, insufficient lattice stability, and poor consistency in large-scale fabrication are the common scientific bottlenecks restricting the performance breakthrough of these two types of devices. Based on the fundamental theories of materials physics, this paper systematically elucidates the ion transport mechanisms of solid-state electrolytes and the dynamic laws of photogenerated carriers in perovskites. Focusing on the key scientific issues including solid-solid interfacial charge transport, interfacial barrier modulation, defect passivation, and lattice stabilization, we review the cutting-edge regulation strategies such as element doping, interfacial modification, in-situ composite fabrication, and the construction of low-dimensional heterostructures. Combined with the industrial practices of Wuhan East Lake High-tech Development Zone (Optics Valley) in the fields of solid-state batteries, perovskite photovoltaics, sodium-ion energy storage, and interfacial regulation equipment, we analyze in depth the technical pathways and practical bottlenecks for the transformation of frontier materials from laboratory research to industrialization. The research results indicate that atomic-level precise interfacial regulation, multi-scale defect engineering, and the integrated fabrication of optoelectronic energy storage devices are the core directions for the future performance breakthrough of such devices. This work can provide theoretical references and research ideas for the study of interfacial physics of new energy materials, the design of high-performance devices, and regional industrial technological innovation in the new energy field.

**Keywords:** New Energy Materials; Solid-State Electrolyte; All-Solid-State Lithium Battery; Perovskite Solar Cell; Interfacial Regulation; Materials Physics; Wuhan Optics Valley

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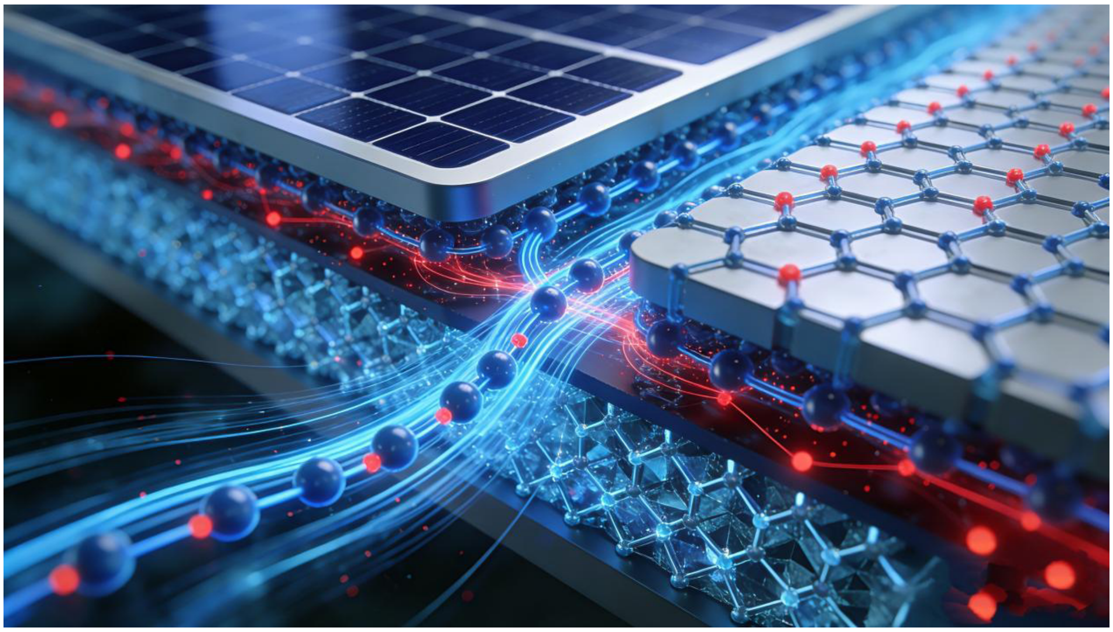
## 1.Introduction

With the accelerated transformation of the global energy structure towards low carbonization, electrification, and intellectualization, high-efficiency energy storage and advanced photovoltaic devices have become the key carriers supporting the global energy revolution. Traditional lithium-ion batteries are limited by the flammability of liquid electrolytes and the approaching upper limit of energy density, making it difficult to meet the high-safety and high-specific energy requirements of next-generation power batteries and grid energy storage [1]. All-solid-state lithium batteries replace flammable organic liquid electrolytes with inorganic or polymer solid-state electrolytes and can be matched with metallic lithium anodes, with a theoretical energy density exceeding 500 Wh $kg^{-1}$. This technology fundamentally solves the risk of thermal runaway and is recognized as the most promising technical route for industrialization in the field of new energy storage [2].

In the photovoltaic field, the photoelectric conversion efficiency of crystalline silicon batteries is gradually approaching the theoretical limit, while perovskite solar cells have achieved a rapid efficiency breakthrough by virtue of their inherent advantages, such as a high light absorption coefficient, long carrier diffusion length, tunable band gap, and low-temperature solution processability. The efficiency of perovskite-based tandem solar cells has exceeded 33%, making them the mainstream direction of next-generation high-efficiency photovoltaic technology [3]. However, both solid-state batteries and perovskite devices are plagued by a core bottleneck: the interfacial issue. The solid-solid interface between the electrode and electrolyte of ASSLBs contains contact voids, space charge layers, and side reaction layers, leading to high interfacial impedance and low lithium-ion transport efficiency [4]; a large number of defect states exist at the grain boundaries and surfaces of perovskite films, triggering severe non-radiative recombination and ion migration, which results in a sharp attenuation of device efficiency and long-term stability [5]. Essentially, these two types of problems all belong to the research scope of interfacial transport, defect dynamics, and lattice matching in the field of materials physics.

*Fig. 1 Schematic diagram of the integrated structure of perovskite photovoltaic-solid-state energy storage devices*



In Fig. 1, the upper layer is the perovskite photovoltaic panel, which is responsible for light energy capture and initial electric energy output; the middle layer is the two/three-dimensional solid-state electrolyte lattice structure, where the large blue spheres represent mobile ions (e.g., $Li^+$), the small red spheres represent photogenerated carriers or defect sites, and the particle flow indicates the direction of energy/ion transport; the lower layer is the supporting substrate and composite electrolyte network, with the blue and red particle flows representing the transport paths of photogenerated carriers and ions, respectively. This diagram intuitively demonstrates the energy conversion and interfacial regulation mechanism of the optoelectronic energy storage integrated device, reflecting the structural stability and unobstructed ion transport channels of the device.

As a national highland of the optoelectronic information and new energy materials industry in China, Wuhan East Lake High-tech Development Zone (Optics Valley) has gathered a number of cutting-edge enterprises, including Solid-state Ion Energy Technology (Wuhan) Co., Ltd, Dongfeng Yuechuang Technology Co., Ltd, Flexible Electronic Technology Co., Ltd, Wandu Photovoltaics Co., Ltd, Jiuyao Optoelectronics Co., Ltd, Yongjia Photovoltaics Co., Ltd, and Qina New Energy Co., Ltd. A complete innovation chain from core materials and interfacial regulation equipment to photovoltaic/energy storage devices has been formed [6-11], which provides an important practical scenario for the basic research and engineering transformation of new energy materials and devices.

*Fig. 2 Panoramic layout of the new energy optoelectronic energy storage integrated industrial park in Wuhan East Lake High-tech Development Zone*

In Fig. 2, the new energy industrial park takes “perovskite photovoltaics” and “solid-state batteries” as its two core development sectors. The perovskite photovoltaic array on the right side of the figure represents the third-generation new photovoltaic technology, symbolizing a clean energy acquisition approach with high photoelectric conversion efficiency; the solid-state battery energy storage unit on the left side represents the new generation of energy storage technology with high safety and high energy density, which effectively solves the intermittency problem of photovoltaic power generation. Fig. 2 intuitively presents the complete energy application chain, from the photoelectric conversion of photovoltaic modules and electric energy storage by solid-state batteries to intelligent scheduling and distribution in the park, fully reflecting the leading advantages of Wuhan Optics Valley in the research and development and large-scale industrial implementation of advanced energy materials.

Combined with the international cutting-edge research progress from 2023 to 2026 and the industrial technology development direction of Wuhan Optics Valley, this paper systematically discusses the interfacial physical regulation mechanisms, material design strategies, and device performance optimization methods of solid-state electrolytes and perovskite photovoltaic devices, with an emphasis on precise interfacial regulation and collaborative innovation of optoelectronic energy storage systems.

# 2.Interfacial Physical Mechanism of Solid-State Electrolyte Materials and All-Solid-State Lithium Batteries

## 2.1 Classification and Ion Conductivity Comparison of Solid-State Electrolytes

Solid-state electrolytes are mainly divided into four major systems: oxide-based, sulfide-based, polymer-based, and composite solid-state electrolytes, each with distinct structural characteristics and electrochemical performance.

Sulfide-based electrolytes exhibit the optimal ionic conduction capacity, polymer-based electrolytes have prominent flexibility but relatively low ionic conductivity at room temperature, and composite solid-state electrolytes can achieve balanced comprehensive performance by combining the advantages of different electrolyte systems. In fact, garnet-type $Li_7La_3Zr_2O_{12}$ (LLZO) and NASICON-type LAGP oxide-based electrolytes possess excellent chemical stability and a wide electrochemical window but suffer from low ionic conductivity at room temperature and poor interfacial contact with electrodes [12]. Sulfide-based electrolytes feature ultra-high ionic conductivity and good mechanical ductility, enabling cold pressing forming, and have become the mainstream industrialization route for ASSLBs at present. However, such electrolytes have prominent problems of high sensitivity to water and oxygen and severe interfacial side reactions with electrodes [13]. Polymer-based electrolytes have excellent flexibility and strong interfacial adaptability with electrodes, but their ionic conductivity at room temperature is limited by the segmental motion of polymer chains and thus needs to be improved through inorganic-polymer composite modification [14].

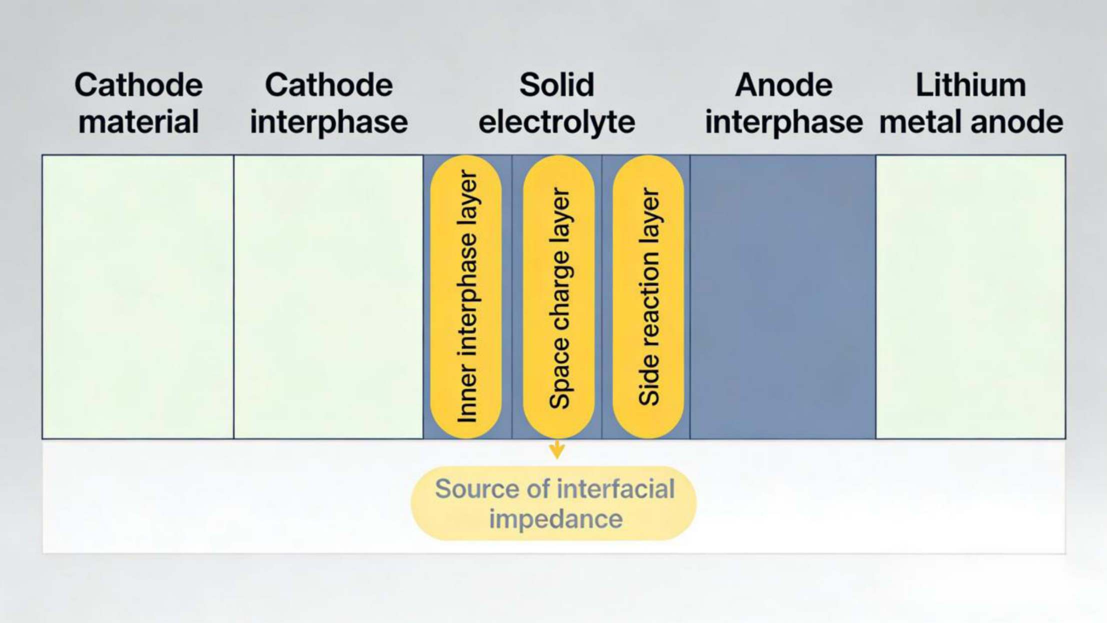
From the perspective of materials physics, lithium ions are mainly transported in solid-state electrolytes through lattice vacancy diffusion and interstitial diffusion, and the grain boundary impedance and defect distribution in the electrolyte bulk directly determine the overall ion transport efficiency [15]. Relying on the achievement transformation of Huazhong University of Science and Technology, Solid-state Ion Energy Technology (Wuhan) Co., Ltd has realized the pilot-scale mass production of polymer-based composite solid-state electrolytes, which provides important material support for the interfacial adaptation of high-performance all-solid-state lithium batteries [16].

## 2.2 Origin of Interfacial Impedance and Physical Model of All-Solid-State Lithium Batteries

The interfacial impedance of all-solid-state lithium batteries is the core bottleneck restricting their ion transport efficiency and comprehensive device performance. Clarifying the formation origin, distribution characteristics, and action mechanism of interfacial impedance is an important prerequisite for conducting research on interfacial regulation strategies. Different from the liquid-phase contact interface of traditional liquid lithium-ion batteries, the solid-solid multiphase interface formed by the cathode, solid-state electrolyte, and metallic lithium anode in ASSLBs forms multiple types and multi-level impedance sources due to lattice mismatch between different materials, differences in electrochemical potential, and uneven contact caused by fabrication processes. Various impedance causes are intertwined and interact synergistically at the interface, further aggravating the hindrance to lithium-ion transport.

To intuitively analyze the impedance composition of the electrode-electrolyte interface of ASSLBs and clarify the corresponding relationship between each component and impedance sources from the microstructural level, this paper constructs a visual model through the method of interfacial impedance decomposition, which clearly presents the formation and distribution law of impedance in the interfacial region. The specific interfacial impedance decomposition characteristics are shown in Fig. 3.

*Fig. 3 Schematic diagram of interfacial impedance decomposition at the electrode-electrolyte interface of all-solid-state lithium batteries*



The interfacial impedance of ASSLBs mainly originates from three key factors: poor physical contact, space charge layer barriers, and interfacial side reaction products. Micron-scale voids exist at the solid-solid interface between electrodes and electrolytes, leading to a significant decrease in the effective ion transport area; the electrochemical potential mismatch between electrodes and electrolytes causes the redistribution of lithium ions at the interface, forming a high-barrier space charge layer that hinders ion migration; irreversible chemical reactions occur between the electrode and electrolyte during charge-discharge cycles, generating an insulating interfacial side reaction layer that further blocks the ion transport path [17]. Electrochemical impedance spectroscopy (EIS) is an effective characterization method for interfacial behavior, which can decompose the total interfacial impedance into bulk impedance, grain boundary impedance, and interfacial transfer impedance, realizing the quantitative characterization of the dynamic behavior of lithium ions in different interface regions [18].

### 2.3 Interface Regulation Strategies for Solid-State Batteries

Interfacial regulation is the core technical path to improve the electrochemical performance of all-solid-state lithium batteries, and the key strategies mainly include element doping and lattice stabilization, interfacial buffer layer modification, in-situ solid-state reaction, and composite electrolyte structure design [19-20]. Flexible Electronic Technology (Wuhan) Co., Ltd has independently developed powder atomic layer deposition (ALD) equipment, which can realize atomic-level conformal coating on the surface of cathode materials and solid-state electrolytes, effectively passivating the interfacial defect sites, significantly reducing the interfacial impedance, and achieving domestic substitution of core equipment [21]. Dongfeng Yuechuang Technology Co., Ltd has built a pilot production line of all-solid-state lithium batteries with a high energy density of 350 Wh $kg^{-1}$, which has promoted the transformation of solid-state battery technology from laboratory material breakthrough to actual vehicle application [22].

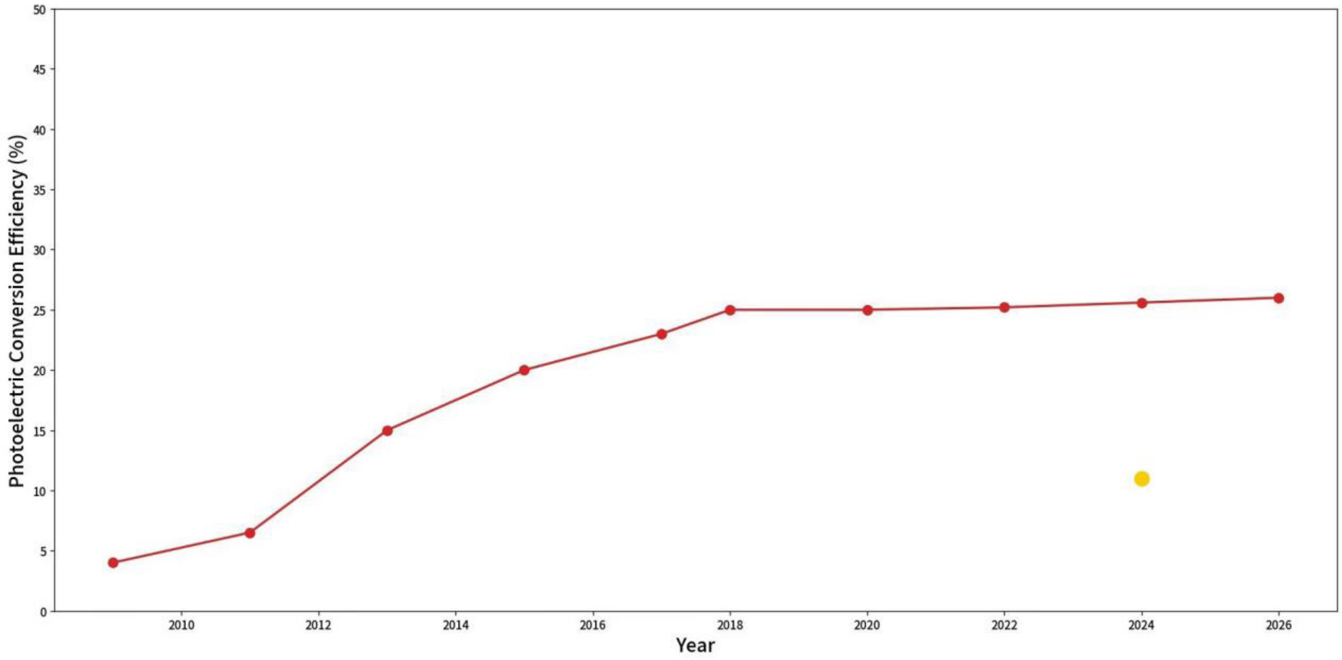
## 3.Physical Characteristics of Perovskite Photovoltaic Materials and Devices

### 3.1 Efficiency Development Curve of Perovskite Solar Cells

Relying on their unique intrinsic material advantages, perovskite solar cells have become one of the fastest technical iteration directions in the global photovoltaic field. Since the first report of perovskite solar cells with a photoelectric conversion efficiency of 3.8% in 2009, their efficiency has achieved a leap-forward improvement through continuous research and innovation, making them the most promising technical route for industrialization among third-generation photovoltaic technologies. Through a series of materials physics optimization methods such as component regulation, defect passivation, and interfacial engineering, researchers have continuously broken through the device efficiency bottleneck. The efficiency of single-junction perovskite solar cells has been continuously refreshed, and perovskite-based tandem solar cells have even broken the efficiency limit of single-junction photovoltaic devices, showing excellent development prospects for industrial application.

As of 2026, the certified photoelectric conversion efficiency of single-junction perovskite solar cells has risen rapidly from 3.8% in 2009 to 26.1%, and the efficiency of perovskite/silicon tandem solar cells has even reached 33%, as shown in Fig. 4.

*Fig. 4 Trend curve of photoelectric conversion efficiency improvement of perovskite solar cells from 2009 to 2026*



Due to their excellent photoelectric characteristics, the efficiency of perovskite solar cells has achieved a leap-forward improvement in more than a decade, far exceeding the development speed of traditional photovoltaic technologies such as crystalline silicon. Perovskite materials have a typical $ABX_3$-type crystal structure, with inherent advantages such as high defect tolerance, a high light absorption coefficient, and a long carrier diffusion length. Their band gap can be continuously adjusted over a wide range through component regulation, which makes them suitable for the fabrication of both single-junction and tandem high-efficiency photovoltaic devices [23]. The formamidinium-caesium-based mixed cation perovskite system can effectively inhibit the phase transition of perovskite crystals and the generation of intrinsic defects during fabrication and operation, and has become the mainstream structure of current high-efficiency and stable perovskite photovoltaic devices [24].

## 3.2 Defect Physics and Interfacial Recombination Mechanism of Perovskite Devices

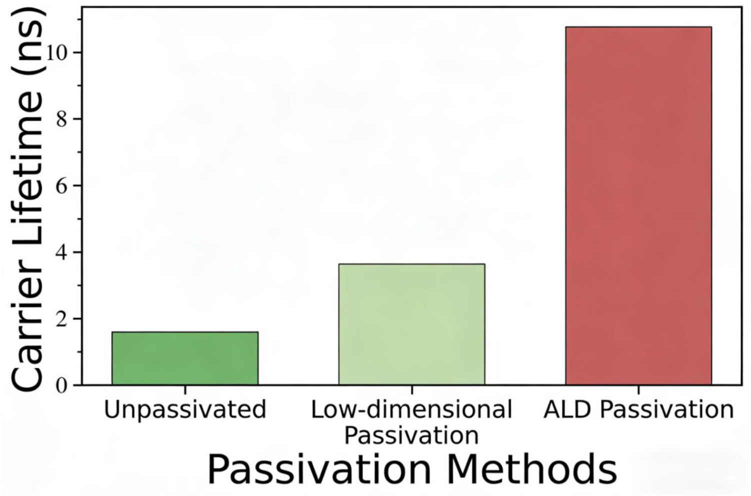
Perovskite materials are typical ionic crystals, and the solution-based fabrication process widely used in industrial production is prone to generate a large number of intrinsic defects such as iodine vacancies, lead vacancies, and surface dangling bonds in perovskite films. These defects act as non-radiative recombination centers, which significantly reduce the open-circuit voltage and fill factor of perovskite solar cells [25]. In addition to the intrinsic defects in the perovskite bulk, the energy level mismatch at the interface between perovskite films and charge transport layers further aggravates the non-radiative recombination of photogenerated carriers, which is a key factor restricting the further improvement of device efficiency and long-term stability [26].

## 3.3 Interface Passivation and Performance Optimization of Perovskite Solar Cells

Interface passivation, crystallization regulation, band engineering, and advanced packaging technology are the core means to improve the photoelectric performance and long-term stability of perovskite photovoltaic devices [27-28]. Among them, interfacial passivation strategies such as low-dimensional perovskite passivation, inorganic oxide interfacial bonding, and self-assembled monolayer modification can effectively passivate the defect sites at the surface and grain boundaries of perovskite films, significantly reduce the defect density, and improve the hydrothermal stability of perovskite devices [29].

Carrier lifetime is a key parameter to measure the photoelectric performance of perovskite films, and its length directly reflects the degree of non-radiative recombination of photogenerated carriers in the films, which is also a core index to verify the effectiveness of interfacial passivation strategies. To quantitatively compare the passivation effects of different interfacial passivation technologies on perovskite film defects, this study takes the unpassivated perovskite film as a blank control and selects two cutting-edge passivation methods widely used in the photovoltaic field, namely low-dimensional perovskite passivation and atomic layer deposition (ALD) passivation, to carry out comparative experiments. The carrier lifetime of perovskite films under different treatment methods is accurately tested and analyzed to intuitively present the actual efficiency of various passivation technologies in inhibiting defect recombination and improving carrier transport characteristics. The specific test results are compared as shown in Fig. 5.

*Fig. 5 Histogram of carrier lifetime comparison of perovskite films before and after defect passivation with different methods*



Effective interfacial passivation can significantly inhibit the non-radiative recombination of photogenerated carriers in perovskite films and improve the long-term stability and photoelectric conversion efficiency of devices. Wuhan Optics Valley has currently formed the most complete perovskite industrial ecosystem in China: Wandu Photovoltaics Co., Ltd has built a GW-level production line relying on the original mesoporous perovskite photovoltaic technology; Jiuyao Optoelectronics Co., Ltd has realized the low-cost mass production of large-area perovskite photovoltaic modules; Yongjia Photovoltaics Co., Ltd has developed all-perovskite tandem solar cells with a photoelectric conversion efficiency exceeding 40%; Yaohua Laser Co., Ltd, Aijiang Technology Co., Ltd, and Yuanlu Optoelectronics Co., Ltd provide core equipment support for the industrialization of perovskite photovoltaic technology [30-35].

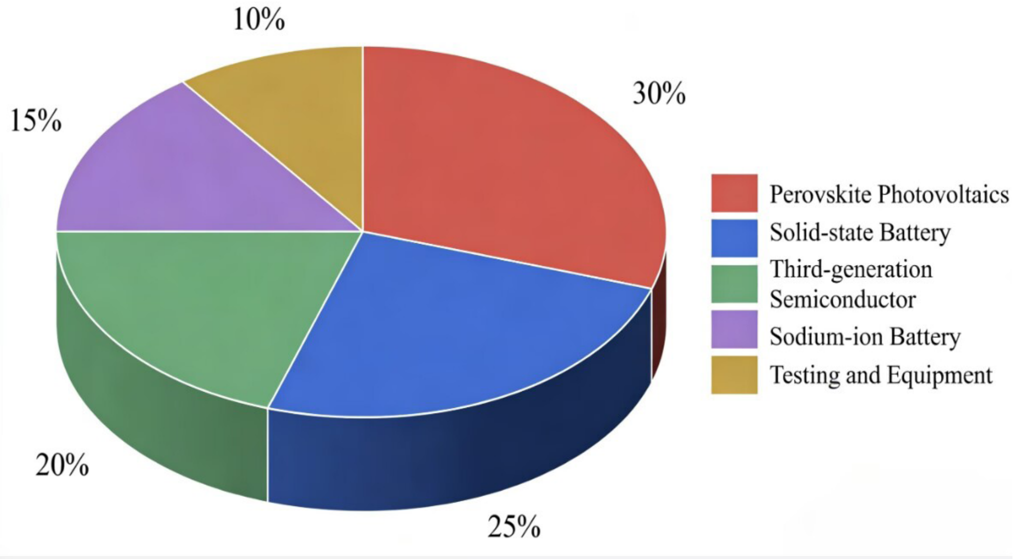
# 4.Analysis of New Energy Materials Industrial Structure in Wuhan Optics Valley

## 4.1 Industrial Distribution of New Energy Materials in Wuhan Optics Valley

Wuhan East Lake High-tech Development Zone (Optics Valley) has formed a diversified and clustered development pattern in the field of new energy materials industry, and the market-dominant sectors are mainly perovskite photovoltaics, solid-state batteries, third-generation semiconductors, sodium-ion batteries, and testing & core equipment manufacturing for new energy devices.

Relying on the core advantages of the optoelectronic information industry with complete industrial chains and strong technological innovation capabilities, Wuhan East Lake High-tech Development Zone has completed the full industrial chain layout in the field of new energy materials and devices, forming a distinctive industrial pattern with photovoltaic energy storage as the core and multi-technical route coordinated development. The industrial proportion and development focus of each subdivision field show distinct differentiation and synergy characteristics, which fully reflect the scientific industrial layout and technological innovation advantages of Wuhan Optics Valley in the field of new energy materials. The specific industrial structure distribution is shown in Fig. 6.

*Fig. 6 Pie chart of the industrial structure of new energy materials and devices in Wuhan East Lake High-tech Development Zone*



Perovskite photovoltaics and solid-state batteries are the core development directions of the new energy materials industry in Wuhan Optics Valley, forming a highly coordinated industrial layout of "core materials - key devices - high-end equipment". Adhering to the development concept of "cutting-edge materials + high-end equipment + scenario application", Wuhan Optics Valley has formed a synergistic development layout in the key directions of solid-state batteries, perovskite photovoltaics, sodium-ion batteries, and third-generation semiconductors. Qina New Energy Co., Ltd has developed high-performance cobalt-free nickel-iron-based sodium-ion cathode materials, reducing the raw material cost by 30% compared with traditional sodium-ion cathode materials; Changfei Advanced Technology Co., Ltd has laid out the research and production of silicon carbide power devices, which provide important device support for high-voltage energy storage and new energy vehicles; Huagong Technology Co., Ltd has promoted the industrialization of green hydrogen production equipment and built a complete photovoltaic-storage-hydrogen integrated energy system [36-38]. These key technical directions are highly consistent with the research content of interfacial physics, advanced material design, and device integration in this paper, which provides important industrial implementation scenarios for the transformation of academic research achievements in the field of new energy materials.

# 5.Summary and Research Prospect

## 5.1 Summary

All-solid-state lithium batteries and perovskite solar cells, as the core devices of next-generation energy storage and photovoltaic technology, face four common scientific problems in the process of performance improvement and industrialization: interfacial transport and barrier regulation, defect physics and lattice stability, microstructure-performance structure-activity relationship, and uniformity in large-scale fabrication. All these problems require in-depth mechanism research and innovative method exploration from the fundamental perspective of materials physics [39-41].

Based on the systematic research on the above scientific problems, this paper first systematically compares the core bottlenecks of solid-state batteries and perovskite devices from a unified perspective of interfacial physics, revealing the common physical mechanisms of interfacial problems in the two types of devices; then it deeply combines the industrial practice of Wuhan Optics Valley, realizing the effective integration of basic theoretical research on new energy materials and regional industrial technological innovation; finally, it puts forward constructive ideas on the future breakthrough path of “atomic-level interfacial regulation + optoelectronic energy storage integration”, which can provide certain reference for subsequent research on advanced new energy materials and high-performance devices.

## 5.2 Future Development Trends

Driven by the global “Dual Carbon” strategy and the demand for high-performance new energy devices, new energy materials will develop towards high stability, low cost, large-area fabrication, and integrated integration in the future. Based on the current research status and industrial demand, atomic-level precise interfacial regulation, in-situ characterization technology of interfacial dynamic behavior, green lead-free perovskite systems, and high-efficiency optoelectronic energy storage coupling devices will become the research focuses in the field of new energy materials and devices.

Located in Wuhan, a national central city with strong scientific and technological innovation capabilities and a complete industrial chain of new energy materials, we can rely on industrial highlands such as Wuhan Optics Valley to accelerate the transformation of cutting-edge scientific research achievements to industrialization, further promoting China to take the leading position in the global research and development and industrialization of the new generation of high-performance new energy devices.

# 6.Conclusion

Taking all-solid-state lithium batteries and perovskite solar cells as the core research objects, this paper systematically discusses the ion transport mechanisms of solid-state electrolytes, the formation mechanism of interfacial impedance, the dynamic laws of photogenerated carriers, and the defect regulation rules of perovskite materials based on the basic theories of materials physics. The key regulation strategies for improving the performance of the two types of devices are summarized, including doping modification, interfacial passivation, heterostructure construction, and in-situ composite fabrication. Combined with the industrial innovation practice of the new energy materials industry in Wuhan Optics Valley, the technical bottlenecks and future development directions in the process of translating frontier new energy materials from laboratory research to industrialization are analyzed in depth.

The research results show that the in-depth analysis of interfacial physical mechanisms and atomic-level precise interfacial regulation are the core keys to breaking through the performance bottleneck of all-solid-state lithium batteries and perovskite solar cells. The research ideas and regulation strategies proposed in this paper can provide important theoretical reference and technical support for the design of high-performance new energy devices and the technological innovation of the new energy materials industry.

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No

## Conflict of Interests

The authors declare that there is no conflict of interest regarding the publication of this paper.

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