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Analysis of Solid-state Battery Principles and Basic Paths

Hongyu Zou

College of Materials Science and Engineering, Beijing University of Chemical Technology, Beijing, China
zouhyhiro@163.com

Abstract. Solid-state batteries (SSBs) replace the liquid electrolyte in liquid batteries with solid-state electrolytes, which effectively improve energy density, safety, and service life. Currently, solid-state electrolytes mainly include three types: oxide-based electrolytes, sulfide-based electrolytes, and polymer-based electrolytes. The challenges they face include interface impedance, dendrite growth, and cost issues. In the future, it is expected that by enhancing material performance, improving interface stability, and optimizing preparation processes to reduce costs, solid-state batteries will be widely applied in fields such as electric vehicles and energy storage systems. This paper adopts a literature review method to study the principle of solid-state batteries and the development status and challenges of the three major technical routes (oxide, sulfide, and polymer). By analyzing material properties and interface issues, it proposes directions for improving performance and reducing costs, which holds guiding significance for the future development of solid-state batteries.

Keywords: Solid-state Battery, Solid-state Electrolyte, Energy Density, Safety

1. Introduction

Solid-state batteries use solid electrolytes to replace the liquid electrolytes in traditional liquid batteries, thereby improving the overall performance of the batteries. The advantages of solid-state batteries mainly include high energy density, high safety, and a long cycle life. Moreover, the solid electrolytes of solid-state batteries have excellent chemical and thermal stability. Compared with liquid batteries, solid-state batteries are less likely to decompose in the reaction at the interface between electrode materials and electrolytes, and can withstand higher voltages. This significantly improves the energy density and output power of the batteries. At the same time, while maintaining good mechanical properties, solid-state batteries also optimize the contact stability at the interface between electrolytes and electrodes [1-3].

Despite the significant advantages of solid-state batteries, the technical challenges they face cannot be ignored. The ionic conductivity of solid electrolytes needs to be further improved to match that of traditional liquid electrolytes. However, various types of electrolyte materials encounter challenges to varying degrees in practical applications, such as dendrite formation, interface stability, and manufacturing process issues. In the future, the development direction of solid-state batteries will focus on enhancing the conductivity and electrochemical stability of materials, as well as improving the economic efficiency of processing technologies. Solid-state batteries are expected

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to be widely applied in electric vehicles and energy storage systems, driving the development of next-generation energy technologies [1-4]. This paper adopts a literature review method to systematically analyze the principles of solid-state batteries and the three major technical routes (oxide, sulfide, and polymer). The research content covers material properties, challenges, and solutions, aiming to clarify the development direction of solid-state batteries, which is of great significance for applications in fields such as electric vehicles and energy storage systems.

2. The three major technical routes of solid-state batteries

2.1. Oxide-based

Oxide-based solid electrolytes have been widely used in the research of solid-state batteries. Their high ionic conductivity and excellent chemical stability make them important candidate materials for realizing high-performance solid-state batteries. The core of oxide solid electrolytes lies in the superionic conductor property in their structure, which allows lithium ions to migrate rapidly in the crystal structure, thereby achieving efficient ionic transport. Common oxide solid electrolytes include LLZO ($Li_7La_3Zr_2O_{12}$), LATP ($Li_{1.3}Al_{0.3}Ti_{1.7}(PO_4)_3$) and LLTO. These materials exhibit superior electrochemical performance and stability within a wide potential window.

However, due to the small contact area of the solid-solid interface, the problem of interface impedance is prominent, which directly affects the overall performance and service life of the battery [5]. By optimizing the chemical and physical properties of the electrolyte-electrode interface such as introducing an interface regulation layer or adopting surface coating technology the interface impedance can be effectively reduced, and the cycle stability and safety of the battery can be improved. Studies have shown that introducing oxide coatings such as $LiNbO_3$, $LiNbO_3$, $Li_4Ti_5O_{12}$, or Al_2O_3 on the electrode surface can significantly enhance the electrochemical performance of solid-state batteries [3,6].

In addition, the preparation process and engineering optimization of oxide solid electrolyte materials are another important direction of research. By improving synthesis methods—such as the solid-state reaction method, sol-gel method, and high-temperature sintering method—electrolyte materials with high purity and high density can be obtained. These methods play a crucial role in regulating the microstructure of materials and can significantly enhance ionic conductivity and mechanical strength. For instance, by optimizing the sintering conditions of LLZO ceramics to make their density reach over 95% and achieve interface chemistry compatible with Li metal, their application potential in solid-state batteries can be effectively improved [6].

Although oxide-based solid electrolytes exhibit outstanding performance in certain aspects, their high density and brittleness impose certain limitations on their application in production. Therefore, oxide solid electrolytes are compounded with polymer electrolytes to achieve performance complementarity by leveraging the flexibility of polymers and the high ionic conductivity of oxides —for example, composite materials of LATP and PEO (polyethylene oxide). This composite strategy can not only enhance the mechanical properties of the electrolyte but also further reduce interface impedance and improve the overall performance of the battery by adjusting the composite ratio and interface compatibility [1].

In summary, the research on oxide-based solid electrolytes in solid-state batteries is of great significance. Through the optimization of material synthesis processes, the application of interface modification and composite strategies, their electrochemical performance and application prospects can be significantly enhanced. However, oxide-based solid electrolytes still face many challenges in

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practical applications, and continuous exploration and innovation are required to promote their large-scale application in solid-state batteries with high energy density and high safety [3].

2.2. Sulfide-based

Sulfide-based solid electrolytes have made significant progress in the research of all-solid-state batteries in recent years, with their ionic conductivity reaching 10-2S/cm, which is comparable to that of traditional liquid electrolytes. This type of electrolyte not only has high ionic conductivity but also, thanks to its soft texture and high plasticity, facilitates the assembly of all-solid-state batteries. However, materials made of sulfides are relatively fragile and prone to cracking, which prevents batteries from functioning properly and limits the development of related technologies [1,3]. Based on the various excellent properties of sulfide electrolytes, different manufacturers have launched relevant samples. Studies have shown that sulfide-based solid-state batteries are gradually moving towards a technology maturity level of 4 to 5. For example, the Hongqi R&D Institute has successfully assembled a sulfide-based all-solid-state battery cell with a large capacity of 10 Ah, and its cycle life exceeds 2,000 times. This development marks a new milestone in sulfide-based all-solid-state batteries in terms of achieving high specific energy cathodes/anodes and air-stable electrolytes [1].

In conclusion, sulfide-based solid-state batteries have shown broad application prospects due to their characteristics of high ionic conductivity and ease of assembly. However, to achieve large-scale production, issues such as stability and electrolyte fragility still need to be addressed. Future research should focus on the development of interface protection layers and the exploration of new synthesis methods to promote the further maturity of sulfide-based all-solid-state battery technology [7].

2.3. Polymer-based

Polymer-based solid-state batteries hold an important position in the field of solid-state battery technology. The main advantages of polymer solid electrolytes lie in their mechanical flexibility, easy processability, and good interfacial contact with electrode materials—characteristics that enable them to perform excellently in different types of solid-state batteries.

However, polymer solid-state batteries still face several challenges in practical applications. The first is the issue of conductivity: the ionic conductivity of polymer electrolytes is much lower than that of liquid electrolytes, which results in poor performance under conditions of high energy density and fast charge-discharge. One of the main approaches to addressing this problem is to form polymer composite electrolytes by incorporating inorganic nanoparticles, thereby enhancing conductivity. Studies have shown that adding an appropriate amount of oxide or sulfide nanoparticles can effectively improve the conductive performance of polymer electrolytes, as well as enhance the cycle stability and low-temperature performance of batteries.

When conducting research on polymer-based solid-state batteries, attention must be paid to the interfacial stability between the electrolyte and the electrode. Interface issues usually arise from incompatibility between the electrolyte and the electrode, which in turn leads to problems such as increased impedance and capacity fading. Additionally, polymer electrolytes may undergo structural degradation during long-term use, which requires the use of chemical modification or cross-linking technology to enhance the mechanical strength and stability of the electrolyte.

In the design of polymer-based solid-state batteries, the battery assembly process and manufacturing costs also need to be considered. Due to the good flexibility of polymer solid

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electrolytes, their processing technology is relatively simple, and they have good compatibility with existing lithium battery manufacturing equipment—factors that help reduce production costs and enable large-scale mass production. However, to achieve higher energy density and longer cycle life in practical applications, polymer solid-state batteries still require further development in areas such as material design, interface optimization, and process improvement.

Overall, polymer-based solid-state batteries have secured a place in solid-state battery technology due to their unique advantages, but their long-term development still requires overcoming a series of technical challenges. In the future, through the interdisciplinary integration and continuous innovation, polymer solid-state batteries will achieve greater breakthroughs in aspects such as conductivity, interfacial stability, and cost control, further promoting the advancement and application of solid-state battery technology [8].

3. Polymer-based

3.1. Characteristics of solid-state batteries

As a next-generation battery technology, solid-state batteries exhibit unique technical characteristics by replacing organic liquid electrolytes with solid electrolytes. First and foremost, the high energy density of solid-state batteries is one of their notable advantages. Theoretically, solid-state batteries can achieve a higher output power density, which is partly attributed to the rapid diffusion characteristics of lithium ions in solid electrolytes and their high ionic conductivity. These properties enable the batteries to demonstrate higher efficiency and stability during charging and discharging processes. Under ideal conditions, the energy density of solid-state batteries is significantly higher than that of traditional liquid batteries, allowing them to store more electrical energy in a smaller volume.Secondly, another key characteristic of solid-state batteries lies in their exceptional safety performance. Compared with traditional liquid lithium-ion batteries, solid-state batteries do not rely on flammable liquid electrolytes, which fundamentally significantly reduces the risks of internal short circuits and thermal runaway within the battery. The wide electrochemical window of solid electrolytes enables them to be used in conjunction with high-voltage cathode materials, thereby further enhancing the overall energy density of the battery. Under extreme conditions, solid-state batteries can also maintain good stability, eliminating the safety hazards caused by the leakage of liquid electrolytes [2]. Solid-state batteries also show potential in structural design and manufacturing processes. Since there is no need to package liquid electrolytes, the battery design methods are more flexible, making it possible to realize new forms and highly intensive manufacturing processes. For example, in the optimization of the contact interface between electrodes and electrolytes, the design of a dynamic compaction structure can effectively reduce the charge transfer resistance of the battery and significantly improve the actual capacity of the battery [3]. This compact design integrates active materials, solid electrolytes, and conductive additives, making full use of every part of the materials and effectively enhancing the overall performance of the battery.

Therefore, solid-state batteries, with their high energy density, high safety, and flexible manufacturing processes, have become representative of next-generation battery technology. These technical characteristics of solid-state batteries not only indicate their broad prospects in the energy storage field but also pose new challenges and requirements for existing battery systems. By deeply understanding and exploring the technical characteristics of solid-state batteries, their future development potential will be even broader, enabling them to better meet diverse application needs.

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3.2. Challenges faced

The challenges in the development of solid-state batteries are mainly reflected in two aspects: materials and applications. First of all, although oxide solid electrolytes have high mechanical strength, they are relatively brittle, which is unfavorable for handling and production. In particular, it is highly challenging to fabricate oxides into ultra-thin films with a thickness of less than 10 microns. Meanwhile, such ultra-thin films are prone to breaking during mechanical processing, resulting in a reduction in the yield rate of the battery production process [3,6]. Secondly, a major issue faced by solid-state batteries in practical applications is their compatibility with lithium metal. When the solid electrolyte comes into contact with lithium metal, it undergoes an unstable reaction, which leads to a decrease in the effectiveness of the electrolyte [3]. Furthermore, a long-standing challenge for solid-state batteries is suppressing the growth of lithium dendrites. Even in solid-state systems, lithium dendrites may still grow along the defects or interfaces of solid electrolytes, leading to short-circuit issues. In experiments, it has been observed that lithium metal tends to grow between the grain boundaries of solid electrolyte particles, thereby causing internal short circuits [3]. This type of short circuit shortens the battery's lifespan and may pose safety hazards during use.

In the face of these challenges, researchers have proposed several solutions. For instance, they enhance the chemical stability between the electrolyte and lithium metal by adding a protective coating on the electrolyte surface, or adopt a multi-layer structure to improve the mechanical strength and stability of the interface. However, the practical effectiveness and feasibility of these methods still need to be verified through extensive experiments. Additionally, further innovation is required in the manufacturing processes of solid-state batteries to enable large-scale production of high-quality products [3,9]. Finally, for large-scale commercial applications, the cost issue is also a major obstacle that must be addressed. Due to the complexity of the materials and manufacturing processes of solid-state batteries, the current cost is relatively high. In the future, it will be necessary to reduce costs by developing economically viable new materials and simplifying manufacturing processes, thereby making solid-state batteries more competitive.

3.3. Future outlook

The development potential of solid-state batteries lies in their ability to address the safety hazards of liquid electrolytes while enabling energy storage systems with higher energy density and longer lifespan. Solid-state batteries utilize solid electrolytes, which not only reduce the risk of battery self-ignition but also allow the use of lithium metal with higher energy density as the anode, thereby significantly enhancing the overall performance of the battery [10]. Solid-state batteries also show potential in structural design and manufacturing processes. Since there is no need to package liquid electrolytes, the battery design is more flexible, making it possible to achieve new forms and highly intensive manufacturing processes. The electrolyte design of solid-state batteries places greater emphasis on chemical stability and ionic conductivity. Through the use of inorganic and polymer composite materials, efficient ion transport channels can be established at different phase interfaces, and this multi-component synergy further optimizes the performance of the battery [3].

Based on the material properties of solid-state batteries, oxide-based solid-state batteries, due to their high electrochemical stability and excellent mechanical strength, are expected to further optimize their performance in the future by improving the ionic conductivity of electrolytes and reducing interfacial impedance, thereby expanding their application in large-scale energy storage systems. On the other hand, sulfide-based solid-state batteries are attracting widespread attention owing to their relatively high ionic conductivity and good interfacial compatibility. Through in-

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depth research on the electrochemical stability and cycling performance of different sulfide materials, breakthrough progress is expected to be achieved, enabling their wide application in future electric vehicles and portable electronic devices. In addition, polymer-based solid-state batteries have attracted extensive research due to their flexibility and processability. In the future, by developing polymer electrolytes with high ionic conductivity and enhancing the stability of polymer-electrode interfaces, their overall performance can be improved, allowing them to occupy an important position in wearable devices and flexible electronic products.

In the future, garnet-structured solid electrolytes may become one of the research hotspots in solid-state batteries. Due to their high ionic conductivity and wide electrochemical window, such materials exhibit excellent performance potential. The key lies in adjusting their chemical composition and microstructure to improve compatibility and stability with electrode materials, thereby achieving longer battery lifespan and higher energy density.

The future development directions of solid-state batteries include improvements in multiple aspects. For instance, future efforts will focus on optimizing the performance of solid electrolyte materials, enhancing the stability of battery interfaces, and developing new manufacturing processes to reduce costs and improve production efficiency. Meanwhile, the compatibility of solid-state batteries with existing battery systems also requires in-depth research to achieve broader applications. In the long run, the development of solid-state batteries is expected to drive technological progress in fields such as electric vehicles and portable electronic devices, enhance their performance and safety, and thus achieve greater social and economic benefits [11].

Solid-state batteries have emerged as representatives of next-generation battery technology, thanks to their high energy density, high safety, and flexible manufacturing processes. These technical characteristics of solid-state batteries not only indicate their broad prospects in the energy storage field but also pose new challenges and requirements for existing battery systems. By deeply understanding and exploring the technical characteristics of solid-state batteries, their future development potential will become even broader, enabling them to better meet diverse application needs.

Overall, the future development of solid-state batteries will rely on continuous breakthroughs and innovations in materials science. For example, the introduction of two-dimensional materials, nanomaterials, or composite materials is expected to further enhance the overall performance of batteries. In addition, advanced characterization technologies and theoretical calculation methods will also play a crucial role in revealing the intrinsic properties of materials and their interfacial behaviors, thereby providing theoretical guidance and an experimental basis for the development of new solid-state batteries. Through the collaborative efforts of the scientific research and industrial sectors, solid-state batteries are expected to achieve large-scale applications in the fields of energy storage and electric vehicles in the future, and exert a profound impact on multiple fields such as smart grids and energy internets [12].

In general, as a next-generation energy storage technology, solid-state batteries demonstrate tremendous application potential and development prospects through a series of innovations in materials and engineering technologies. Although they still face many challenges at the current stage, with the continuous deepening of research, solid-state batteries will surely occupy an important position in the future energy field [13].

4. Conclusion

This paper systematically reviews the working principles of solid-state batteries and the current development status as well as challenges of their three major development routes, namely oxide-

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based, sulfide-based, and polymer-based solid electrolytes. By means of a literature review, this paper conducts an in-depth analysis of the advantages of solid-state batteries in improving energy density, safety, and cycle life, and discusses in detail the characteristics of various types of solid electrolyte materials and the problems they face, such as interfacial impedance, dendrite growth, and cost issues. Solid-state batteries significantly enhance energy density, safety, and cycle life by replacing liquid electrolytes with solid electrolytes. The chemical and thermal stability of solid electrolytes is superior to that of liquid electrolytes, enabling solid-state batteries to perform excellently in withstanding high voltages and improving energy density. Regarding oxide-based solid electrolytes: This type of material has been extensively studied due to its high ionic conductivity and good chemical stability. However, the main challenge lies in the interfacial impedance caused by the small solid-solid interface contact area. The interfacial impedance can be effectively reduced by optimizing the chemical and physical properties of the interface, such as by introducing an interface modification layer or adopting surface coating technology. For sulfide-based solid electrolytes: Sulfide solid electrolytes exhibit high ionic conductivity and are easy to assemble into all-solid-state batteries. Nevertheless, their material brittleness and cost issues restrict their large-scale application. Future research should focus on the development of interface protective layers, the exploration of new synthesis methods, and cost reduction. As for polymer-based solid electrolytes:, their mechanical flexibility and easy processability play an important role in solid-state batteries. However, their ionic conductivity is relatively low, which needs to be improved by introducing inorganic nanoparticles to form composite electrolytes. Meanwhile, interfacial stability and structural degradation during long-term use are also issues that need to be addressed.

This paper only analyzes the three major development routes of solid-state batteries. However, due to limitations in length and research depth, it fails to cover all the latest research findings and technological advancements. The discussion on certain new types of solid electrolyte materials (such as garnet-structured solid electrolytes) is relatively brief. Additionally, this paper lacks experimental verification; its research is mainly based on a literature review and lacks support from detailed experimental data and results, which imposes certain restrictions on the reliability and accuracy of some conclusions.

The development of solid-state batteries can focus on deepening basic research, strengthening fundamental studies on solid electrolyte materials, and exploring ion transport mechanisms, interface reaction mechanisms, and methods for optimizing electrochemical performance. These efforts can provide a solid theoretical foundation for the commercial application of solid-state batteries. Meanwhile, experimental research should be enhanced to verify the performance of different solid electrolyte materials through experiments and explore their application effects in actual battery systems. In addition, interdisciplinary integration can be promoted. The research on solid-state batteries involves multiple disciplines such as materials science, electrochemistry, and mechanical engineering. In the future, efforts should be made to strengthen interdisciplinary integration and collaborative innovation to jointly advance the development and application of solid-state battery technology.

In conclusion, solid-state batteries will occupy an important position in the development of the energy sector in the future. Although many difficulties are encountered at present, with the deepening of research and the advancement of science and technology, solid-state batteries are expected to become a safer, more efficient, and more widespread way of electrical energy storage.

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