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Research and Development of Solid-State Batteries and its Application

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Abstract. The overconsumption of fossil fuels has led to energy and environmental crises, making the development of safe and efficient energy storage systems a key research focus. Lithium-ion batteries are widely applied due to their high energy density, yet conventional liquid electrolytes suffer from flammability and leakage issues. All-solid-state lithium batteries (ASSBs), which replace liquid electrolytes with solid counterparts, exhibit superior safety and potential for next-generation applications. This review summarizes the characteristics and advances of oxide, sulfide, and polymer solid electrolytes, with comparative analysis of thermal stability, ionic conductivity, interfacial resistance, and mechanical strength. Results indicate that sulfide electrolytes achieve the highest conductivity but poor stability; oxide electrolytes offer excellent safety yet rigid interfacial contact; polymer electrolytes provide outstanding flexibility and processability but limited room-temperature conductivity. Composite electrolytes, through complementary effects, show promise in enhancing interfacial stability and overall performance. Moreover, industrial efforts by Toyota, Volkswagen, and Solid Power highlight accelerating commercialization. In conclusion, despite challenges in interface control, ion transport, and scalable fabrication, solid-state batteries are expected to achieve breakthroughs and drive the future development of electric vehicles.

Keywords: Oxide electrolytes; Sulfide electrolytes; Polymer electrolytes; Composite electrolytes; Electric vehicles.

1. Introduction

The excessive consumption of fossil fuels has triggered increasingly severe energy crises and environmental issues. Consequently, the development of stable and efficient energy conversion and storage devices has become a central research focus. Among various energy storage technologies, lithium-ion batteries have emerged as a prominent choice due to their high energy density and relatively environmentally friendly properties, establishing themselves as the dominant power source for portable electronic devices and electric vehicles. However, as application scenarios and environments continue to expand, safety concerns have become increasingly prominent. Particularly in the context of the demand for higher energy density, the development of traditional lithium-ion batteries is facing severe challenges. The root cause lies in the flammable and highly corrosive nature of the widely used organic liquid electrolytes, which not only restricts the application of batteries in high-safety scenarios such as aerospace and deep-sea equipment but also severely limits further improvements in energy density and cycle life.

It is under such technological bottlenecks that all-solid-state lithium batteries have gradually become a focal point for both academia and industry, regarded as a critical direction for next-generation energy storage systems. The author believes that the most fundamental innovation of all-solid-state batteries lies in the complete replacement of liquid electrolytes with solid electrolyte materials. This transformation not only significantly enhances thermal stability and safety but also holds the potential to break the existing energy density limits, extend cycle life, and provide new pathways for high-safety, high-performance energy storage. From the perspective of material types, solid electrolytes can currently be classified into three main categories: oxides, sulfides, and polymers, each with distinct characteristics. Oxide systems exhibit excellent electrochemical stability and a wide electrochemical window, making them suitable for high-voltage applications. Sulfide electrolytes

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currently boast the highest ionic conductivity, particularly ideal for high-rate applications, though their poor atmospheric stability remains an issue to be addressed. Polymer electrolytes, on the other hand, offer good flexibility and excellent interfacial contact properties, demonstrating unique potential for large-scale fabrication and flexible batteries. The author suggests that the future development of solid-state batteries may not be dominated by a single material system but is more likely to move toward composite and functionally integrated directions—for instance, achieving complementary advantages among different materials through multilayer structures or surface modifications.

However, the widespread commercialization of solid-state batteries still faces numerous obstacles. Key limiting factors, as identified by the author in literature reviews, include insufficient interfacial contact, suboptimal ionic conductivity, and complex manufacturing processes, all of which hinder large-scale practical application [1]. In recent years, the emergence of composite electrolyte systems has provided innovative pathways to address these critical issues. By integrating multiple materials and optimizing structural design, composite strategies achieve synergistic effects, effectively advancing solid-state batteries toward commercial viability. Meanwhile, leading global automotive manufacturers and energy companies are increasingly investing in and focusing on this technology, highlighting its significant potential for future applications.

Accordingly, this review systematically summarizes the latest progress in solid-state battery research, with a focused examination of the properties, development, and persistent challenges of diverse solid electrolyte materials. It also evaluates the application potential of these systems within the electric vehicle industry. Through a critical comparison of the advantages, limitations, and emerging trends across various electrolyte platforms, this work aims to provide valuable perspectives on future research priorities and scalable production routes for solid-state batteries.

2. Different types of solid-state batteries

Solid electrolytes are generally classified into three categories: polymer, oxide, and sulfide solid electrolytes [2].

Sulfide electrolyte: It is the absolute leader in ionic conductivity and its performance is closest to that of traditional liquid electrolytes, making it an ideal choice for achieving high energy density and fast charging and discharging.

Oxide electrolyte: It excels in safety and stability. With the widest electrochemical window, extremely high mechanical strength and thermal stability, it is the safest and most reliable option.

Solid polymer electrolyte: It has unparalleled advantages in processing performance and interface compatibility. Its excellent flexibility, low interface impedance and simple solution processing method make it the most suitable for flexible devices and large-scale production. As seen in Table 1.

Table 1. Performance Comparison of Solid-State Electrolytes [3].

Performance Metric	Thermal stability	Electrochemical Window	Interfacial Impedance	Ionic Conductivity	Li-ion transference	Mechanical Strength
Oxide Electrolyte	>500°C	>5 V	100-500Ω·cm^2	10^{-3}–10^{-4} S/cm	0.99	5-15GPa
Sulfide Electrolyte	300-400°C	3-4 V	50-200 Ω·cm^2	10^{-3}–10^{-4} S/cm	0.99	1-3GPa
Polymer Electrolyte	150-250°C	0.1-0.5 V	10-50 Ω·cm^2	10^{-4}–10^{-6} S/cm	0.5-0.8	0.1-0.5 GPa

2.1. Oxide Solid-State Electrolytes

Oxide solid-state electrolytes are typically classified into two types: crystalline and amorphous (glassy). Representative crystalline materials include NASICON, perovskite, garnet, and LISICON, which have been systematically explored in the field of ionic conductivity research. In the glassy system, LiPON has received particular attention and is currently widely used in related research on thin-film batteries.[4]. Oxide lithium-ion conductors generally exhibit greater stability toward ambient air and high temperatures, facilitating easier handling during manufacturing and operation. Furthermore, oxide electrolytes stand out due to the wider availability of raw materials. Consequently, oxide solid-state electrolytes have experienced rapid development in recent years.

2.2. Sulfide solid-state electrolyte

Sulfide solid electrolytes represent a category of inorganic solid electrolytes characterized by the substitution of sulfur for oxygen. This replacement of O^{2-} with S^{2-}, which possesses a larger ionic radius and higher polarizability, induces two critical modifications in crystalline oxide electrolytes: first, it expands the unit cell, creating wider pathways that enhance Li^+ mobility; second, it weakens the electrostatic interaction between the host framework and Li^+ ions, resulting in an increased concentration of mobile charge carriers. Consequently, sulfide electrolytes exhibit much higher ionic conductivity than oxide electrolytes [5], and they can generally be classified into glassy, glass–ceramic, and crystalline types. Despite these advantages, sulfide electrolytes still suffer from several limitations, including complex synthesis requirements, poor charge–discharge stability, low environmental stability, and inadequate interfacial contact with electrodes. Although their ionic conductivity is high, these issues hinder practical application [1]. To tackle these challenges, researchers have proposed strategies such as incorporating suitable additives to develop novel sulfide electrolyte systems that combine high ionic conductivity with improved air stability. At the same time, optimizing the interface between the electrode and the electrolyte remains crucial [6]. Specific approaches include increasing the effective contact area, developing more compatible electrode materials, or reducing interfacial resistance through surface modifications. From the author's perspective, while these research directions are promising, real-world application will likely require more interdisciplinary collaboration and advances in manufacturing processes. For instance, it is not just about improving material performance—factors like cost, scalability, and environmental impact also need to be taken into account. Academia often focuses on boosting performance metrics, while industry tends to prioritize stability and cost-effectiveness. Striking a balance between these two perspectives may be the key to enabling the widespread commercial adoption of sulfide-based solid-state batteries. All in all, sulfide solid electrolytes show great potential, but they still face considerable practical challenges. Continued in-depth research addressing these limitations will be essential to eventually realize the reliable application of all-solid-state batteries.

2.3. Polymer Solid Electrolytes

Polymer-based solid electrolytes (SPEs) consist of a polymer matrix and alkali metal salts. The polymer framework not only provides structural support and flexibility but also effectively dissolves lithium salts and forms continuous ion transport pathways. Owing to their favorable mechanical compliance and interfacial compatibility, SPEs enable intimate contact with electrodes, significantly reducing interfacial resistance. As such, they represent a highly promising class of solid electrolyte materials [7]. From the author's perspective, the key advantage of SPEs lies in their dual functionality—combining ion transport and mechanical support in an integrated structure. Nevertheless, their development faces fundamental challenges: achieving both high ionic conductivity and robust mechanical strength remains difficult, as enhancing conductivity often compromises mechanical performance. Furthermore, interfacial stability during long-term cycling and the feasibility of large-scale manufacturing remain critical bottlenecks for commercialization. Future efforts should focus on the design of amorphous flexible polymers, organic-inorganic composite strategies, and interfacial engineering to facilitate the practical application of SPEs.

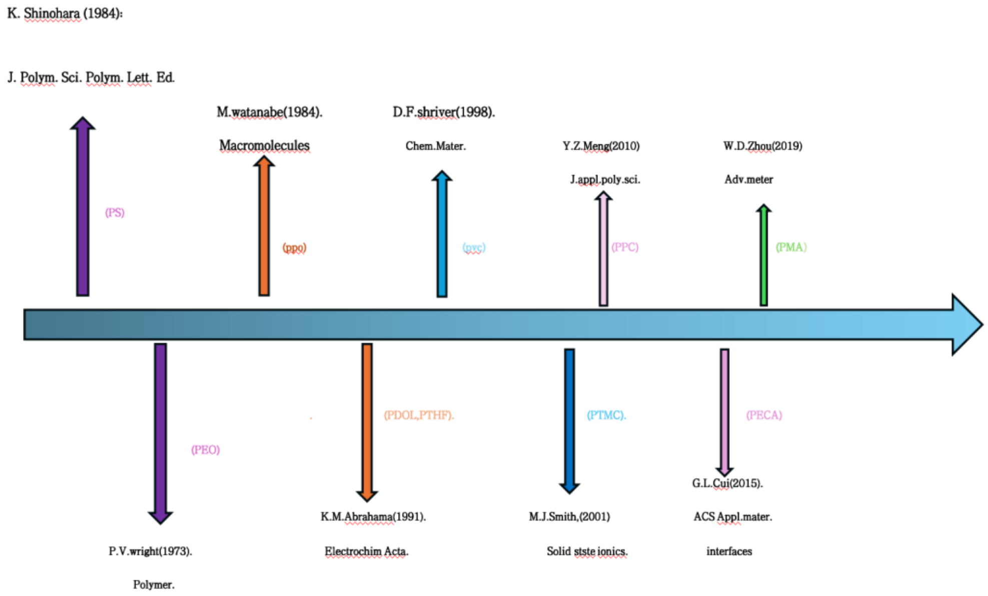

Fig. 1 The Evolution and Progress of Solid Polymer Electrolytes [8-10].

Notes: PS refers (Polysiloxane), PEO refers Poly(ethylene oxide), PPO refers Poly(β-propylene oxide), PDOL refers Poly(dioxolane), PTHF refers Poly(tetrahydrofuran), PVC refers Poly(vinyl carbonate)/Poly(vinylene carbonate), PPC refers Poly(propylene carbonate), PMA refers Poly(maleic anhydride), PTMC refers Poly(trimethylene carbonate), PECA refers Poly(ethylcyanoacrylate)

Research on polymer electrolytes has undergone continuous evolution over the past five decades. The pioneering work was conducted by Wright in 1973, who first reported polyethylene oxide (PEO) as a solid polymer electrolyte, demonstrating its ability to dissolve salts and conduct ions. This seminal discovery laid the foundation for subsequent investigations. In the 1980s, significant progress was made in the development of polymer electrolytes, with key contributions from Watanabe (1984) on β-poly(propylene oxide) (PPO) and Shriver (1988) on polymer–salt complexes, which greatly enriched the understanding of ion conduction mechanisms in polymeric systems. The following decade witnessed the emergence of new polymer host materials, such as poly(dioxolane) (PDOL) and poly(tetrahydrofuran) (PTF) introduced by Abraham (1991), which offered enhanced ionic conductivity and mechanical flexibility compared to earlier systems—an achievement once considered unimaginable.

Since the early 2000s, the research focus has gradually shifted toward environmentally friendly and functionally customized polymer systems. Smith (2001) developed poly(trimethylene carbonate) (PTMC), and subsequent research by Meng (2010) focused on PVC-based electrolyte systems. In recent years, increasing attention has been paid to interfacial compatibility and multifunctional design. For instance, Cui (2015)'s work on poly(butyl cyanoacrylate) (PBCA) and Zhou (2019)'s exploration of poly(maleic anhydride) (PMA) have demonstrated promising application prospects for these materials in solid-state electrochemical devices, indicating substantial potential for future development.

Throughout this evolution, polymer electrolytes have diversified from early polyether-based systems to include various structural families such as carbonates, acrylates, and anhydrides. This ongoing expansion reflects sustained progress in achieving higher ionic conductivity, improved mechanical properties, and optimized interfacial behavior, thereby facilitating the integration of polymer electrolytes into advanced energy storage technologies, including lithium batteries and modern solid-state devices. It is worth noting that the development of the field exemplifies a typical trajectory from fundamental discovery to applied innovation. Recent studies have increasingly emphasized practical issues such as interfacial stability and environmental compatibility, indicating a shift from a purely performance-oriented approach toward a balance between performance and applicability. However, polymer electrolytes still face challenges such as the trade-off between ionic conductivity and mechanical strength, interfacial compatibility with electrode materials, and the cost of large-scale production. To truly achieve commercialization in applications such as all-solid-state batteries, breakthroughs in material modification (e.g., composite electrolytes), structural design (e.g., three-dimensional conductive frameworks), and interface engineering are still required. Meanwhile, introducing emerging research methods such as machine learning and high-throughput screening into the field may accelerate the discovery and optimization of new material systems. From the author's standpoint, research on polymer electrolytes not only demonstrates a clear lineage and developmental trajectory but also reflects a notable characteristic of adapting to evolving application demands. Its future development will undoubtedly emphasize multidisciplinary collaboration and system integration, thereby playing a more critical role in energy storage and conversion.

3. Limitations and challenges of Solid-state electrolytes in Lithium Batteries

3.1. Physic mechanical Stability

A key factor governing the cycle life and overall durability of all-solid-state batteries is the interfacial physico-mechanical stability between the electrode and the solid electrolyte. Insufficient stability often results in structural stress accumulation at the interface, which continues to intensify during electrochemical cycling and ultimately deteriorates the electrochemical properties of the cell.

Oxide-based solid electrolytes are generally considered chemically stable against lithium metal. Nevertheless, their intrinsically high elastic modulus leads to limited interfacial contact with the cathode during deformation, thereby forming structural defects and increasing interfacial resistance. In contrast, sulfide-based electrolytes exhibit higher mechanical softness, which facilitates improved interfacial contact. However, cathode materials inevitably undergo periodic lattice expansion and contraction during charge–discharge cycles, resulting in significant volume changes. Such changes diminish the effective interfacial contact area, increase interfacial resistance, and impair electrochemical performance.

To address these challenges, several strategies have been proposed. Suppressing the volume changes of cathode materials during cycling, reducing the particle size, constructing three-dimensional (3D) electrode/electrolyte architectures [11], and introducing soft interfacial buffer layers have all been shown to release accumulated structural stress effectively [12]. These approaches contribute to lowering interfacial resistance, forming more stable solid–solid contacts, and thereby enhancing the physicomechanical stability and electrochemical performance of all-solid-state batteries.

3.2. The challenges encountered by SPE in electrochemistry

Oxide-based solid-state batteries have attracted considerable attention due to their wide electrochemical window and excellent thermal stability. However, their high elastic modulus often leads to insufficient interfacial contact, resulting in large interfacial resistance and compromised electrochemical performance. In contrast, sulfide-based solid-state batteries exhibit ionic conductivities comparable to those of liquid electrolytes, making them ideal candidates for high-power output. Nevertheless, their relatively poor electrochemical stability, tendency to decompose under high voltages, and unstable interfaces with electrode materials limit their long-term cycling performance [13].

The electrochemical stability window in polymer electrolytes is largely defined by the energy gap separating the highest occupied molecular orbital (HOMO) and the lowest unoccupied molecular orbital (LUMO). In order to increase the oxidation resistance of solid polymer electrolytes (SPEs), researchers have put forward two main approaches.

First, the construction of a stable cathode–electrolyte interphase (CEI). If a stable ion-conducting coating layer or interfacial passivation layer can be formed between the SPE and the cathode material, it can effectively prevent direct contact between the SPE and the high-valence transition metal ions on the surface of cathode active materials. This effect contributes to a more stable electrode-electrolyte interface by mitigating parasitic reactions, thereby significantly enhancing the cycling durability of solid-state lithium batteries. Second, molecular structure engineering to lower the HOMO energy level of the SPE, thereby widening its electrochemical window and enabling compatibility with high-voltage cathode materials. This approach is particularly important for enhancing the energy density of solid-state lithium-metal batteries. For instance, relevant studies conducted at universities have shown that polyester-based polymers, owing to the presence of numerous electron-withdrawing groups (e.g., C=O), exhibit significantly lower HOMO levels than ether-based polymers and thus offer a wider electrochemical window. In addition, the incorporation of strongly electron-withdrawing functional groups, such as fluorine (F) or cyano (–CN), into polymer backbones has also been demonstrated to effectively lower the HOMO energy level of SPEs, thereby enhancing their electrochemical oxidative stability.This example shown in Figure 2.

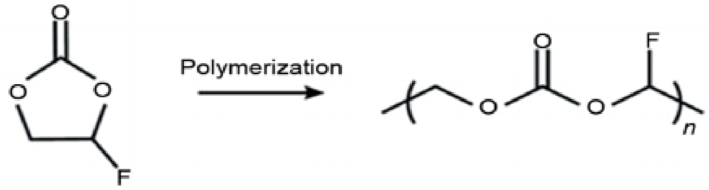

Fig. 2 Molecular Design of High-Voltage Stable Polymer Electrolytes [14]

4. Application

In recent years, major international automobile manufacturers, including Toyota, BMW, Honda, Nissan, Hyundai, Volkswagen, and General Motors, have accelerated their research and industrial deployment of solid-state lithium batteries. For instance, Toyota announced in 2021 that it would unveil its solid-state battery technology alongside a prototype vehicle equipped with such a battery. This prototype demonstrated a remarkable charging advantage, requiring only 15 minutes for a full charge. Toyota scheduled performance testing in 2021 and aims for vehicle integration by 2028.

Honda has established a demonstration/test production line at its R&D center in Sakura City, Japan, for verifying processes such as the ratio of electrode and electrolyte materials, coating, and compaction. It plans to start the test line in early 2025 to promote the maturity of the mass production process. Nissan has also built a solid-state battery pilot production line at its factory in Yokohama to promote the integration of innovative manufacturing technologies and materials in actual battery modules, and to extend the research from molecular material stages to overall battery and automotive applications. As for BMW, its collaboration with Solid Power in the United States is underway: BMW has installed Solid Power's large-format all-solid-state batteries (pure ASSB cells) on the BMW i7 test model for road tests in the Munich area; meanwhile, Nissan is building a prototype line at its battery manufacturing competence center (Cell Manufacturing Competence Center, CMCC) in Parsdorf, Germany, for sample manufacturing and module integration verification of solid-state batteries. It is widely recognized that solid-state lithium batteries, given their superior technical and performance characteristics, are likely to become the mainstream choice for electric vehicles following liquid-based batteries. Nevertheless, the path to industrialization remains hindered by technological and manufacturing challenges. Consequently, collective efforts from across the industry are required to overcome these barriers. Through continuous optimization of material systems and technological innovations, the development of solid-state batteries with higher safety, greater energy density, and improved low-temperature performance can be achieved. Ultimately, such advancements will accelerate the commercialization and large-scale deployment of solid-state lithium batteries in the automotive sector.

5. Conclusion

In summary, although sulfide electrolytes possess high ionic conductivity, they suffer from insufficient chemical stability and certain limitations in processability. Oxide electrolytes also demonstrate relatively high conductivity; however, their rigid interfacial contact and severe side reactions, together with fabrication challenges, significantly restrict their application. By contrast, polymer electrolytes exhibit clear advantages in interfacial compatibility and mechanical processability, yet their low ionic conductivity at room temperature limits the applicable operating range. *To overcome such obstacles, researchers have turned to composite solid electrolytes, a material system considered to hold great potential.* On the one hand, incorporating inert inorganic nanoparticles into polymer electrolytes can effectively improve their overall performance; on the other hand, composites of oxides or sulfides with polymers allow complementary advantages, achieving enhanced ionic conductivity and mechanical strength while maintaining favorable electrode compatibility. Indeed, several already-commercialized solid–liquid hybrid lithium battery systems employ composite solid electrolytes as their core materials.

Looking ahead, the development of solid-state lithium batteries is expected to proceed through a gradual transition from semi-solid and quasi-solid systems toward fully solid-state systems. Nevertheless, realizing this leap requires overcoming a series of challenges, including the simultaneous improvement of ionic conductivity and stability in electrolyte systems, the effective regulation of interfacial issues, and the optimization of scalable fabrication processes. Despite these obstacles, given the strong industrial interest and collaborative research efforts worldwide, continued advances in material design and cell architecture are anticipated to drive breakthrough progress in solid-state lithium batteries and ultimately accelerate their large-scale commercialization.

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