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The Development and Challenges of Solid-State Electrolytes of the Lithium-Ion Batteries

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Abstract. Batteries, as an important carrier for replacing traditional energy sources, have received much attention. Among them, lithium-ion batteries have attracted significant attention and are intensively studied due to their advantages such as high energy density, long lifespan and high working voltage. However, the liquid electrolyte in lithium-ion batteries is prone to fire and explosion, which makes it unsafe. This has led people to focus on and develop solid-state electrolytes. Therefore, this paper systematically reviews the research status of different solid-state electrolytes, with a particular emphasis on oxide solid-state electrolytes, sulfide solid-state electrolytes, polymer solid-state electrolytes, and halide solid-state electrolytes, as well as their current research status and progress. The research has found that due to the low environmental requirements of polymer solid-state electrolytes and the maturity of the industry, they currently hold a dominant position in terms of production volume and application. However, in terms of ionic conductivity at room temperature, it is inferior to other electrolytes and still requires further study. The sulfide electrolyte has extremely high ionic conductivity, but its chemical stability is relatively poor compared to oxide electrolytes. Oxide electrolytes also have outstanding air stability and can be combined with halide electrolytes to form more superior electrolytes. This review systematically examines the development and challenges of solid-state electrolytes, providing strategic references and solutions to accelerate the commercialization of next-generation safe and high-energy-density batteries.

Keywords: lithium-ion batteries, solid-state electrolytes, development prospects

1. Introduction

As the new energy industry develop rapidly, the energy and fuel consumption are increasing, but the most common and popular fuels are non-renewable resources such as coal and natural gas, these kinds of fuels are unfriendly to the environment. The depletion of fossil fuels, coupled with growing environmental concerns such as climate change and air pollution, has accelerated the shift toward electrification in various sectors, particularly in transportation and renewable energy storage.

As a result, the government decide to implement the electrification, the main carrier of this process is the battery, and the most popular battery recently is the lithium-ion battery because of its long life cycle, high working voltage, high energy density, etc [1]. However, the fatal weakness of the lithium-ion battery is the safety issue, traditional lithium-ion battery uses organic liquid

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electrolytes, which inherently possess volatility, flammability, and thermal instability, posing serious safety hazards. Incidents of thermal runaway leading to fires or even explosions are very common, menace user safety and impede the further development of high-energy-density batteries. In addition, the poor compatibility between liquid electrolytes and highly reactive electrode materials leads to issues like dendrite growth and interfacial side reactions, limiting further improvements in battery energy density. Nowadays, the mainstream electrolytes on the market are all liquid electrolytes, although they have numerous advantages, including capable of efficiently transporting lithium ions, high ionic conductivity, providing high voltage and high specific energy for the battery, the safety and environmental issues they bring are nonnegligible. The safety problems like high flammability, thermal runaway and leakage and corrosion could cause dangerous effects. The production of liquid electrolytes is a high-energy chemical process, a major part of the energy are generated from the non-renewable resources, which have a huge influence on the earth. Besides, the process could produce some toxic and harmful chemical waste like the hydrogen fluorine and sulfur dioxide.

To reduce the negative impacts, the battery producers pay more attention to the solid-state electrolytes, solid-state electrolytes provide the potential to overcome the limitations of liquid electrolytes by providing enhanced safety, higher mechanical strength, and strengthen thermal stability. Moreover, they enable to applied for lithium metal anodes, according to theoretical calculations, all-solid-state lithium batteries could achieve energy densities more than twice that of existing liquid batteries, which means it could significantly increase the energy density of next-generation batteries, it could bring revolutionary improvements in the range of electric vehicles and the standby time of electronic devices. The current popular solid-state electrolytes including oxides, sulfides, polymers and halides, each of them has their own advantages, they are facing very different and extremely crucial technical difficulties, find out the specific problem and understand the properties of these materials are significant for the development of the solid-state electrolytes. The solid-state electrolytes still faced several difficulties, issues like low ionic conductivity at room temperature, poor interfacial compatibility with electrodes [2]. Beyond the inherent material limitations, solid-state batteries also face problems in manufacturing processes and cost control [3]. For instance, sulfide electrolytes require entirely dry production environments, significantly increasing production costs; the sintering process for oxide electrolytes is poorly compatible with existing battery production lines; These technical difficulties have made the commercialization of solid-state batteries slower than anticipated.

This paper aims to provide a comprehensive overview of the recent advancements and persistent challenges in the field of solid-state electrolytes. Using the CAS (Compare, Analyze, Summarize) method, it provides a comprehensive evaluation of the properties of different materials, technical advantages, and limitations of the four major categories of solid-state electrolytes: oxides, sulfides, polymers, and halides. By analyzing the latest research advances and industrialization tendencies, hope this study could offers technical references and strategic perspectives for the future development of solid-state electrolytes, and contributes academic and engineering value to promoting the commercialization of safe, high-energy-density solid-state batteries.

2. Solid-state electrolytes

In this section, this essay will discuss the classification, advantages and drawbacks of the mainstream electrolytes on the market. The definition of the solid-state electrolytes is a solid material that, in its solid state, can conduct ions much like a liquid electrolyte, but is virtually an electronic insulator. It is the main component of an all-solid-state battery, used to replace traditional

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liquid or gel electrolytes. The common solid electrolytes can classify into four different types of electrolytes, they are oxide solid electrolytes, sulfide solid electrolytes, polymer solid electrolytes and halide solid electrolytes. .

2.1. Oxides solid electrolytes

The oxide solid-state electrolytes are crystalline or glass-ceramic materials composed of metal oxides. Ion conduction occurs through vacancies or interstitial sites within their crystal lattice. They are typically fabricated through high-temperature solid-state sintering, resulting in rigid, dense ceramic pellets. Their lithium conduction mechanism relies on the hopping of Li-ions within a rigid oxygen-ion framework. The most prominent examples are garnet-type LLZO ($Li_7La_3Zr_2O_{12}$) and NASICON-type LATP ($Li_{1+x}Al_xTi_{2-x}(PO_4)_3$). The oxide solid electrolytes have plenty of advantages, the general benefits are outstanding electrochemical and thermal stability, wide electrochemical window, high mechanical strength, and good air stability facilitating easier handling, but it still have some difficulties need to overcome, such as high interfacial resistance due to rigid solid-solid contact, inherent brittleness, high sintering temperatures increasing cost and complexity, and moderate room-temperature ionic conductivity. There are three major oxide solid electrolytes in the market, they are LLZO ($Li_7La_3Zr_2O_{12}$), NASICON-type LATP ($Li_{1+x}Al_xTi_{2-x}(PO_4)_3$) and Perovskite-type LLTO ($Li_{3x}La_{2/3-x}TiO_3$), they have the different benefits and drawbacks.

2.1.1. Garnet-type LLZO ($Li_7La_3Zr_2O_{12}$)

LLZO (Lithium Lanthanum Zirconate) is a garnet-type solid-state electrolyte material with the chemical formula $Li_7La_3Zr_2O_{12}$. LLZO is arguably the most extensively researched oxide electrolyte due to its unique combination of properties. The first advantage is the excellent lithium metal stability, its thermodynamic stability against lithium metal is superior, effectively preventing detrimental side reactions and enabling long-term cycling. And the second benefit is the wide Electrochemical Window, its stability up to ~6 V allows pairing with high-voltage cathode materials like $LiCoO_2$ and $LiNi_{0.8}Mn_{0.1}Co_{0.1}O_2$. Besides, the high Ionic Conductivity for an Oxide is also beneficial, the doped variants can achieve bulk ionic conductivities around 10^{-4} S/cm at room temperature.

However, the scientists should pay attention to the disadvantages of the LLZO. First of all, the surface contamination is a serious problem, its surface readily reacts with atmospheric CO_2 and H_2O to form Li_2CO_3, which drastically increases interfacial resistance and requires expensive post-synthesis polishing [4]. Another drawback is the high sintering temperature, it requires sintering at around 1200°C, often leading to lithium loss and the need for cumbersome mother-pellet burial techniques, complicating mass production. And the last disadvantage should be care about is the brittleness of the LLZO, the ceramic is prone to cracking, creating pathways for lithium dendrites, producing lithium dendrites is an extremely dangerous situation for the battery, because it will piercing the SEI membrane and further causing battery short circuit or other more serious consequences. The LLZO has the huge potential for solid electrolytes development, it is significant to improve the advantages and overcome the drawbacks. It used in All-Solid-State Batteries, LLZO serves as a critical component in ASSBs, replacing traditional liquid electrolytes.

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2.1.2. NASICON-type LATP ($Li_{1+x}Al_xTi_{2-x}(PO_4)_3$)

LATP refers to Lithium Aluminum Titanium Phosphate, a NASICON-type solid-state electrolyte used in all-solid-state lithium-ion batteries. LATP offers high conductivity and easier sintering than LLZO but suffers from a critical instability issue. This material has numerous benefits, the three major advantages are the high ionic conductivity, easier sintering ability and excellent air stability [5]. The most notable advantage is the high ionic conductivity, it can achieve conductivities up to 10^{-3} S/cm, among the highest in the oxide family, this factor makes the LATP become competitive among solid electrolytes. And easier sintering is another advantage of the LATP, it only requires sinters working at lower temperatures compared to LLZO, it can reduce the cost of production and easier to achieve large-scale production. In addition, the LATP has the excellent air ability, it can handle ambient air conditions better than many other solid-state electrolytes.

But there are still some challenges need to face for the properties of the LATP, such as the LATP has the instability with lithium metal, The Ti ions in LATP is easily reduced by lithium metal to Ti^{3+}, causing rapid degradation and failure. This precludes its direct use with a lithium anode without a protective interlayer. This special property makes all the anodes need to be covered with the protective interlayer, and this will result in the increasing cost of production so become more difficult to have further developments. The second property disadvantage people should focus on is the brittle nature of the LATP. It will share the brittleness common to all ceramic oxides, which means it cannot undergo excessive pressure has led to its insufficient toughness, thereby affecting the stability and quality of the battery. There is still a long way to go before it becomes a popular and high-quality electrolyte. It has several applications, including All-Solid-State Lithium-Ion Batteries, High-Energy Density Batteries and dendrite suppression.

2.1.3. Perovskite-type LLTO ($Li_{3x}La_{2/3-x}TiO_3$)

LLTO stands for Lithium Lanthanum Titanate, a ceramic material used primarily as a solid-state electrolyte in advanced lithium-ion batteries. LLTO was an early frontrunner with very high bulk conductivity but is hampered by severe grain boundary issues. The most significant advantage is the exceptional bulk ionic conductivity, it can reach larger than 10^{-3} S/cm in single crystal or large-grain form, showcasing the potential of oxide materials, which means LLTO has the potential for commercial development.

However, the disadvantages that LLTO has are quite obvious. One of the bad properties is the high grain boundary resistance, the polycrystalline LLTO has very low total conductivity due to highly resistive grain boundaries, negating its bulk advantage, this property makes the LLTO become less competitive between the many kinds of the solid electrolytes. Another drawback is the Ti^{4+} reduction, like LATP, the Ti^{4+} is reduced by lithium metal, making it incompatible [6]. Besides, the LLTO has the complex processing, which means to achieving large-grained or single-crystal films is prohibitively expensive for commercial application. These limitations cause the LLTO hard to become the popular and useful solid electrolyte in the market. The major applications are Solid-State Batteries, Next-Generation Lithium-ion Batteries and Lithium-Sulfur Batteries. LLZO is a leading candidate for solid-state electrolytes, enabling the development of all-solid-state batteries that use lithium-metal anodes. Additionally, its high Li+ conductivity makes it suitable for advanced battery designs that aim for higher energy density and improved safety.

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2.2. Sulfide solid-state electrolytes

Sulfide solid-state electrolytes are characterized by the substitution of oxygen with sulfur, leading to a softer material and weaker Li-ion bonding. This results in extremely high ionic conductivity, often rivaling liquid electrolytes. This electrolyte has several common benefits, like the highest room-temperature ionic conductivity, good mechanical deformability and lower processing temperatures. These benefits make the sulfide solid-state electrolytes very popular among different types of solid electrolytes. However, it still has some common drawbacks, like the extreme sensitivity to moisture (it will be generating toxic H_2S gas), narrow electrochemical stability window (it will prone to oxidation at high voltages), and poor stability against lithium metal. These are the difficulties that sulfide solid-state electrolytes need to overcome.

2.2.1. Argyrodite-type Li_6PS_5Cl

Argyrodite-type Li_6PS_5Cl is a solid electrolyte material with high lithium-ion conductivity, making it a promising candidate for all-solid-state batteries. Argyrodite-type Li_6PS_5Cl has become a benchmark sulfide electrolyte due to its balanced properties and relative ease. Its most prominent advantages consist of three points. Among them, what is very similar to other electrolytes is high conductivity. It exhibits a high ionic conductivity of ~1-3 mS/cm at room temperature. But compared to other electrolytes, the processability of the Li_6PS_5Cl is much better. It can be synthesized at scale via mechanochemical ball milling and forms dense pellets by cold pressing [7], this advantage allows it easier to achieve large-scale production and commercialize. Additionally, the producers improved its moisture stability. Although it remains moisture-sensitive, it is more stable than pure thiophosphates like Li_3PS_4.

However, the Li_6PS_5Cl still has several specific drawbacks, the two main flaws are moderate oxidation stability and generation of H_2S gas. It begins to oxidize around 2.5-3.0 V, requiring stabilization at the cathode interface for use with most common cathodes. This defect is very similar to LATP, it also needs protective coatings on the cathodes to reduce oxidization. Besides, it will still produce toxic H_2S upon exposure to moisture, mandating dry-room production. Li_6PS_5Cl, sometimes in doped or composite forms, is also applied in all-solid-state lithium-ion batteries, particularly those using a Li-S cathode, where its lower electrochemical stability is less problematic. .

2.2.2. LGPS-type ($Li_{10}GeP_2S_{12}$)

$Li_{10}GeP_2S_{12}$ is a class of superionic conductors with extremely high lithium-ion conductivity, making them a crucial component for next-generation solid-state lithium batteries. LGPS shocked the research community with its liquid-like conductivity. Although all kinds of solid electrolytes have the high conductivity, the LGPS has the superionic conductivity, it can achieve an astounding ionic conductivity of 12 mS/cm at room temperature, setting a high bar for all solid-state electrolytes [8]. This property is outstanding among the same type of electrolytes; it means this solid electrolyte can have the same conductivity as the liquid electrolytes.

However, the drawbacks are really common. It has extreme moisture sensitivity, because it is highly reactive with air/water. Besides, the LGPS contains the expensive metal germanium in the material, so precise machinery is required, and the raw materials for this item are also very expensive, resulting in excessively high production costs. It can use in All-Solid-State Batteries, LGPS and its derivatives are promising candidates for solid electrolytes in next-generation all-solid-

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state lithium batteries. Their compatibility with lithium metal anodes is crucial for realizing high-energy-density lithium metal batteries.

2.2.3. $Li_2S{\cdot}30P_2S_5$ glass-ceramic

This represents a classic glass-ceramic sulfide electrolyte formed by heat-treating a glassy precursor. Just like the common advantages of all the kinds of sulfide electrolytes, this LSPS has high conductivity and formability. The glassy phase allows for easy shaping, and subsequent crystallization yields a conductivity of ~10^{-4} S/cm. Unlike the LGPS, the raw materials of LSPS are common and accessible, result in cheaper in cost and price. Don't underestimate the advantage of low cost, because this is a crucial factor determining whether this material can be widely and extensively utilized and produced. However, it also has all the common drawbacks of sulfide solid-state electrolytes. As with all sulfides, it requires strict moisture control and can be even more reactive with cathode materials than crystalline sulfides.

2.3. Polymer solid-state electrolytes

Polymer solid-state electrolytes consist of a polymer matrix dissolved with a lithium salt. Ion transport is coupled to the segmental motion of the polymer chains, occurring primarily in the amorphous phase above the glass transition temperature. It has numerous advantages, such as superior flexibility, ease of processing into thin films, wonderful interfacial contact, low cost, and high safety such as non-flammable. These advantages all represent the potential for it to become a high-quality solid electrolyte. However, it has some undeniable drawbacks that might affect the performance of the battery. Like the low ionic conductivity at room temperature poor mechanical strength at elevated temperatures, limited electrochemical window and mediocre stability against lithium metal. These drawbacks have prevented this substance from being the best solid electrolyte.

2.3.1. PEO-LiTFSI

PEO-LiTFSI refers to a solid polymer electrolyte (SPE) system for lithium batteries, composed of Poly (ethylene oxide) polymer and the lithium salt Lithium Bis(trifluoromethanesulfonyl)imide (LiTFSI). Poly (ethylene oxide) with LiTFSI salt is the archetypal polymer electrolyte. Decades of research have led to a deep understanding of its chemistry and electrochemistry, which means the producer have the proven technology in the production of the PEO-LiTFSI. It has significant advantages in both performance and manufacturing. It has the wonderful film-forming ability, which can easily solution-cast into large, thin, and robust membranes. Additionally, it has the good thermal and electrochemical stability, LiTFSI, the salt component, possesses nice thermal and electrochemical stability, contributing to a stable and long-lasting electrolyte system [9].

However, it still has several limitations. The low ionic conductivity at room temperature is a significant problem, the high crystallinity of PEO at ambient temperatures hinders polymer chain motion and ion transport, resulting in low ionic conductivity. This issue might affect the efficiency of the battery and the energy density. Another problem will influence the battery is the PEO-LiTFSI has the potential for ion aggregation. Large quantities of triple ions or higher aggregates of ions can form, reducing the overall Li^+ transference number and hindering performance. It is not only applied in lithium-ion batteries and lithium-sulfur batteries, but it can also be use as Ternary PEO/PLA Blends. To address the limitation of PEO in high-temperature applications (above 70 °C), PEO can be blended with other polymers like poly(l,l-lactide) (PLA). Incorporating LiTFSI into these

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PEO/PLA blends further enhances their use at high temperatures by providing mechanical reinforcement and excellent electrochemical performance.

2.3.2. PAN-based electrolytes

PAN-based electrolytes are solid or gel-polymer electrolytes that use polyacrylonitrile (PAN) as a primary component, leveraging its strong mechanical strength, electrochemical stability [10], and ability to interact with and dissociate ion salts via its polar nitrile groups to facilitate ion transport. It has some benefits like mechanical strength and nice compatibility. PAN's inherent strength can be beneficial for creating robust and durable electrolyte components. Besides, it exhibits good compatibility with high-voltage cathode materials and can be formulated to improve its interaction with lithium metal anodes, as seen in composite electrolytes.

However, the disadvantages are also important factors that could affect the production process, Ii has interfacial issues. For instance, it has unstable interphases. PAN-based electrolytes can undergo uncontrolled reactions with lithium metal anodes, leading to the formation of unstable interfaces and hindering battery performance. This property will damage the the lithium-ion battery and further cause some serious results. Additionally, it has complex conduction mechanism. At present, our understanding of this thing is not profound, and the technology is not yet mature, ion transport is less understood. For the applications, it can use in Solid-State or Gel Polymer Batteries. PAN's ability to conduct Li+ ions makes it suitable for fabricating solid-state Lithium Ion Battery and gel polymer electrolytes by forming membranes with organic solvents and lithium salts.

2.3.3. Composite Polymer Electrolytes (CPEs) with LLZO fillers

Composite Polymer Electrolytes (CPEs) with $Li_7La_3Zr_2O_{12}$(LLZO) fillers are solid-state electrolyte materials for lithium-metal batteries, combining the mechanical strength and flexibility of a polymer with the high ionic conductivity of the LLZO ceramic filler. CPEs represent the most promising direction for polymer electrolytes, combining a polymer matrix with ceramic fillers. It has plenty of advantages including enhanced ionic conductivity, high thermal and electrochemical stability etc. he LLZO fillers form a 3D network or percolation channels within the polymer matrix, facilitating faster and more efficient transport of Li+ ions [11]. Besides, LLZO contributes to the overall stability of the composite electrolyte, enhancing its thermal stability and widening its electrochemical stability window.

However, it still has several difficulties. For example, it has the possibility of fatigue softening. Under the stress of charge and discharge cycles, composite electrolytes can undergo fatigue softening, a gradual decrease in their compressive modulus over time, which compromises their structural integrity. Another impact is influencing the battery performance. The long-term stability of the battery is often limited by capacity fading after hundreds of charge-discharge cycles, this significantly shortens the battery's lifespan and usage duration.

2.4. Halide solid-state electrolytes

Halide solid-state electrolytes are a type of solid material composed of metal and halogen elements that function as an electrolyte in solid-state batteries, enabling ionic conduction to facilitate the battery's chemical energy storage and release. Halide solid-state electrolytes are a rapidly emerging class that combines the high conductivity of sulfides with the high-voltage stability of oxides. They are typically composed of lithium, a metal cation (Y, Zr, In, Sc), and a halogen (Cl, Br, I). It has

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unique combination of high ionic conductivity (~10^{-3} S/cm), high oxidation stability (>4 V), enabling direct use with high-voltage cathodes without protective coatings and good mechanical sinterability [12]. But it is sensitivity to moisture, contains high cost of raw materials and has poor reduction stability against Li metal. It can apply in many kinds of batteries. Firstly, it enable use in Lithium Metal Batteries. Halide electrolytes provide high ionic conductivity and superior oxidative stability, which is crucial for the safe and efficient use of highly reactive lithium metal anodes. Secondly, it can use in Sodium-Ion Batteries. Halide solid electrolytes are a promising alternative for solid-state sodium batteries. Furthermore, it can apply in Solid-State Sodium-Sulfur batteries, Sodium-Oxygen Batteries and Solid-State Lithium-Organic Batteries.

3. The future prospects of solid electrolytes

Although the commercialization of solid-state electrolytes faces numerous challenges, its future prospects are very promising. Future improvements will focus on technological innovation, cost reduction, and clear market trends.

3.1. Technological innovation

The future breakthroughs will focus on solving core issues like interfacial impedance and stability. Composite electrolytes will become popular, combining flexible polymers with highly conductive sulfides or stable oxide nanoparticles to synergistically enhance mechanical properties, conductivity, and interfacial contact. Interface engineering is also crucial. Techniques like Atomic Layer Deposition can build ultra-thin, stable artificial interlayers to effectively suppress side reactions and reduce interfacial resistance. Furthermore, exploring new materials, such as Li-rich anti-perovskites and using machine learning for high-throughput screening, will accelerate the discovery of electrolyte systems with superior performance and cheaper elements.

3.2. Cost reduction

Large-scale cost reduction is key to market penetration. Raw material substitution is a core strategy, such as replacing expensive Germanium (Ge) and Tantalum (Ta) with more abundant Tin (Sn) and Antimony (Sb) and developing Germanium-free sulfides and Yttrium-free halides. Process innovation is equally important. Developing continuous, large-scale, low-energy manufacturing processes like tape casting and roll-to-roll printing will replace expensive high-temperature sintering and dry-room operations, significantly lower the manufacturing costs.

3.3. Development trends

Future development will follow a clear path. In the short term, oxide electrolytes will be prioritized for specific sectors with extreme safety demands (e.g., aerospace, special equipment). In the medium term, polymer composite electrolytes are expected to be first adopted in consumer electronics and electric vehicles due to their processing advantages. In the long term, as technology matures and costs fall, high-performance sulfide and halide electrolytes will ultimately become the mainstream choice for the electric vehicle battery market, ushering in a new era of ultra-safe, high-energy-density batteries.

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4. Conclusion

This article's systematic study on solid-state electrolytes reveals that the current solid-state electrolyte industry has already established a relatively solid foundation, and among the four mainstream electrolytes, they are developing concurrently, each with its own advantages and disadvantages.

Polymer electrolytes have the best flexibility, simple production process, and the lowest cost, and are the only type that has achieved large-scale commercial application, currently being used in fields such as consumer electronics. However, their core drawback is that the room-temperature ionic conductivity is too low, severely limiting its use in high-demand scenarios such as electric vehicles.

Oxide electrolytes have the most balanced overall performance, with high ionic conductivity, excellent stability, and a wide electrochemical window, and are recognized as one of the most promising technological routes for use in electric vehicles. However, due to its relatively hard texture, there are problems of poor solid-solid interface contact and high impedance between it and the electrode, which are the core challenges that need to be overcome currently.

Sulfide electrolytes have the highest ionic conductivity among all categories and can even be comparable to liquid electrolytes. They have a soft texture, which is conducive to processing and forming. However, this material is extremely sensitive to air and water, and when exposed to water, it will produce highly toxic hydrogen sulfide gas, thus presenting significant engineering challenges and high production costs, severely hindering its commercialization process.

Halide electrolytes, as an emerging technological path, possess high ionic conductivity and show good compatibility with high-voltage positive electrode materials, but they usually cannot be matched with lithium metal negative electrodes. This system is currently still in the early stage of research, and its maturity is far lower than the other three types.

Looking ahead, the development of all-solid-state batteries may tend towards a composite electrolyte solution, by integrating the advantages of different materials (such as using polymers to improve interface contact and employing oxides to enhance stability), rather than relying on a single material system.

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