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Solid-state Lithium-ion Batteries: Applications and Challenges

1.1 Background and Introduction

Organic liquid lithium-ion batteries have been widely used in many sectors of the national economy (such as portable electronic devices, electric vehicles, and large-scale energy storage, among others) and are gradually expanding into specialized application fields like deep-sea, deep-space, deep-earth, polar regions, individual soldier equipment, drones (military and civilian), and outer space exploration. The introduction of the national "Dual Carbon" strategy has further provided an excellent development opportunity for secondary electrochemical energy storage technologies, typically represented by lithium-ion batteries.

However, organic liquid lithium-ion batteries pose safety hazards, primarily due to the following:

1. Mainstream carbonate solvents are generally volatile, have low flash points, are flammable and explosive at elevated temperatures, and possess certain toxicity, which limit their operating temperature range.
2. Dendrites readily form on the anode surface, potentially piercing the separator and causing a short circuit between the cathode and anode, leading to battery fires. When the anode surface is uneven, repeated charge–discharge cycles can lead to excess lithium accumulation and deposition on the anode surface, forming lithium dendrites. These dendrites may penetrate the microporous separator, connect to the cathode electrode, and cause an internal short circuit.

Meanwhile, as the demands for energy density and safety performance of lithium-ion batteries in mobile electronic devices like smartphones and notebooks, as well as in electric vehicles and large-scale energy storage, continue to rise, traditional liquid lithium-ion batteries inevitably undergo side reactions during charging and discharging. These reactions not only affect battery lifespan but also raise safety concerns due to the flammable organic electrolyte and multiple industry incidents of vehicle spontaneous combustion, causing public apprehension about lithium battery safety.

From January to July 2023, several spontaneous combustion incidents involving new energy vehicles attracted the attention of national regulators. On July 28, 2023, the Equipment Industry Development Center of the Ministry of Industry and Information Technology issued the "Notice on Carrying Out the 2023 New Energy Vehicle Safety Hazard Investigation Work," which deployed tasks for investigating safety hazards in new energy vehicles and specified clear deadlines and content requirements for reporting fire incidents.

Analyzing the root causes of battery safety hazards and revealing the underlying failure mechanisms are prerequisites for constructing highly safe battery systems. In commercial liquid lithium-ion batteries, polyolefin separators with poor dimensional stability and flammable, leak-prone organic electrolytes are considered the primary factors leading to thermal runaway. However, research indicated that improving separator thermal stability and employing flame-retardant electrolytes can only mitigate the battery's exothermic behavior to a certain extent and cannot fundamentally prevent thermal runaway [1, 2]. Tracing back to the origin, a profound understanding of the evolution path of the chain exothermic reactions during thermal runaway is crucial from a macroscopic perspective [3]. Based on an in-depth analysis of battery exothermic characteristics, Cui and coworkers from the Qingdao Institute of Bioenergy and Bioprocess Technology, Chinese Academy of Sciences, proposed that the thermal compatibility between battery materials (electrode materials, electrolytes, additives, etc.) is crucial for battery safety. The team explored the failure mechanism of high-nickel NMC batteries through coupled in situ/ex situ methods at multiple levels, from materials to the battery. Using an isotope titration–mass spectrometry online gas detection device, they identified the presence of lithium hydride (LiH) on the graphite anode of NMC batteries and confirmed that the poor thermal stability between this component and the electrolyte is the main factor inducing the chain self-exothermic behavior of the battery. Furthermore, using a self-developed double-reaction sphere test device for in situ detection of gas shuttling behavior during thermal runaway, they demonstrated that H_2 generated by LiH on the anode side can shuttle to the cathode side, accelerating intense exothermic reactions and causing thermal runaway [4–6]. Based on this research, it was found that the chemical composition of the anode interface layer and its derivatives significantly impact battery thermal runaway. Therefore, effectively suppressing the accumulation of LiH and the generation of H_2 on the anode side is key to intrinsically solving battery safety issues from a materials perspective.

The intrinsic properties of traditional liquid lithium-ion battery materials indicate that they cannot meet the stringent future requirements for energy density, cycle life, and safety of high-performance devices. Consequently, replacing flammable and explosive liquid electrolytes with non-hydrogen-containing solid-state electrolytes is expected to fundamentally solve the hydrogen generation problem in lithium batteries, cut off the initiation source of thermal runaway, fabricate lithium battery systems with inherently high safety and reliability, and enable the safe design of high-energy-density power batteries. Thus, solid-state lithium batteries have become a research and development hotspot (Figure 1.1).

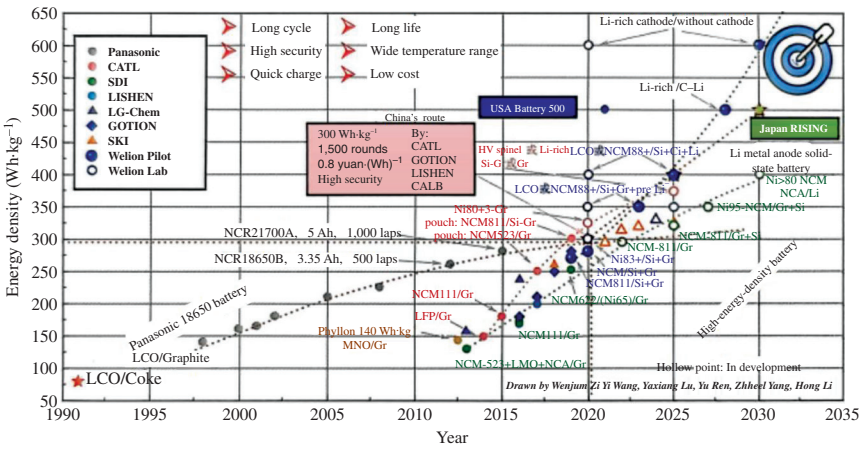

Figure 1.1 Solid-state lithium batteries enhance the safety, energy density, cycle life, and other characteristics of the battery system [7].

1.2 Electrochemical Principles

1.2.1 Working Principle of Solid-state Batteries

As a revolutionary energy storage system, the basic structure of a solid-state battery primarily consists of four core components: the cathode, solid-state electrolyte, anode, and current collectors. The cathode typically employs lithium transition-metal oxides (e.g., NCM, NCA), lithium iron phosphate (LFP), or high-capacity lithium-rich manganese-based materials. The solid-state electrolyte, acting as the "soul" of the entire battery, fulfills the dual mission of conducting lithium ions while blocking electrons. The anode can be materials like graphite or silicon–carbon, but the most revolutionary prospect lies in directly using a metallic lithium anode. The current collectors are similar to conventional batteries, with aluminum foil for the cathode side and copper foil for the anode side. The core feature of this structure is that the ion conduction medium is entirely solid-state. This fundamental change not only greatly simplifies the battery structure but also makes possible high-energy-density system architectures like bipolar stacking (integrating multiple cells in series within a single package). In terms of working principle, solid-state batteries macroscopically still follow a "rocking-chair" mechanism similar to liquid lithium-ion batteries, where lithium ions shuttle back and forth between the cathode and anode via intercalation and deintercalation. Specifically, during charging, an external power source applies a voltage, driving electrons (e^-) from the cathode through the external circuit to the anode. Simultaneously, lithium ions (Li^+) deintercalate from the cathode material lattice, enter and migrate through the solid-state electrolyte toward the anode side, finally reaching the anode where they combine with electrons and are stored as atoms embedded in the anode material or deposited on the metallic lithium surface, thereby converting electrical energy into

chemical energy. During discharge, this process reverses: Li at the anode undergoes oxidation, losing electrons to become Li^+, while electrons flow back to the cathode through the external circuit, performing work. Li^+ ions traverse the solid-state electrolyte again, return to the cathode, and reinsert into the lattice, releasing the stored chemical energy as electrical energy. The key distinction in the entire process is that ion conduction occurs entirely within the solid medium, eliminating the inevitable solvation/desolvation processes present in liquid electrolytes. Furthermore, the solid-state electrolyte itself integrally fulfills the dual functions of ion conduction and physical separation of the cathode and anode.

1.2.2 Electrochemical Principles

If the working principle describes the macroscopic process of "where lithium ions come from and where they go," the electrochemical principles profoundly reveal the microscopic mechanisms and core scientific questions of "how they migrate and interact" within the solid-state system. First, the ion conduction mechanism of the solid-state electrolyte is the foundation for all this, and its ionic conductivity is a core performance metric. Conduction mechanisms vary across material systems: oxide electrolytes (e.g., LLZO) rely on lattice interstitial or vacancy mechanisms, where Li^+ "hops" through predefined crystal channels—they are chemically stable but rigid. Sulfide electrolytes (e.g., $Li_{10}GeP_2S_{12}$ [LGPS]) utilize the weak binding effect due to the large radius of sulfur ions, enabling migration via vacancy mechanisms or even a "push–pull" coordinated motion between Li^+ and the lattice framework, achieving ultrahigh ionic conductivity comparable to liquids, but they are extremely sensitive to the environment. Polymer electrolytes (e.g., polyethylene oxide [PEO]-based) conduct ions relying on chain segment motion; Li^+ migrates within the flexible polymer through coordination and de-coordination with polar groups, offering advantages like good interfacial contact but typically low room-temperature ionic conductivity. The fundamental differences in the conduction mechanisms of these three types of electrolytes directly determine their distinct application prospects and technical challenges.

However, the true "Achilles' heel" of solid-state batteries lies not in the bulk electrolyte itself, but in the solid–solid interfacial electrochemistry formed between the electrolyte and the electrodes. This issue manifests at three levels. First, interfacial contact: point contact between rigid solids cannot achieve perfect wetting like liquids, resulting in small effective contact area and high interfacial impedance, which further deteriorates under the volume changes of electrode materials (e.g., silicon, lithium) during cycling. Second, interfacial chemical stability: most solid-state electrolytes, when in contact with high-potential cathodes or low-potential metallic lithium anodes, undergo thermodynamically driven decomposition reactions, forming an interfacial layer. This interphase plays a dual role: if it is ionically conductive but electronically insulating, it can kinetically stabilize the interface (similar to a good solid electrolyte interface [SEI] film); conversely, if its ionic conductivity is poor, it becomes a barrier for ion transport, drastically increasing impedance and consuming active lithium. Third, lithium dendrite growth: this is not exclusive to

liquid systems. In solid electrolytes, dendrites can grow along grain boundaries, cracks, or other defects, or be caused by electrons penetrating into the electrolyte reducing Li^+, or even use the immense mechanical stress generated by deposition to "wedge open" the electrolyte, ultimately leading to short circuits.

It is these complex interfacial problems that bring both enormous opportunities and challenges for the application of the metallic lithium anode—the ultimate choice. The theoretical appeal of solid-state batteries largely stems from their combination with the metallic lithium anode, which possesses an extremely high theoretical specific capacity and the most negative electrochemical potential. Ideally, a robust solid-state electrolyte should suppress dendrites and provide a uniform Li^+ flux, enabling uniform lithium deposition/stripping. However, in reality, the immense volume change associated with the "hostless" nature of metallic lithium poses a devastating test for solid–solid interfacial contact; simultaneously, its strong reducibility causes reactions with almost all solid-state electrolytes, making interfacial stability extremely difficult to maintain. Therefore, realizing the application of metallic lithium anodes shifts the core scientific problem beyond the electrolyte material itself to the synergistic regulation of interfacial conduction, mechanical contact, and electrochemical stability.

1.3 Development History

1.3.1 Development History of Solid-state Batteries

The development history of solid-state batteries is not a brand-new field that has suddenly emerged in recent years to address the bottlenecks of liquid lithium-ion batteries, as people usually imagine. Instead, it is a magnificent scientific and technological epic that spans nearly two centuries, full of the spirit of scientific exploration, evolves together with materials science and basic electrochemical theories, and experiences ups and downs and revivals. The germination of this idea can be traced back to the era of Physicist Michael Faraday in the early 19th century. In the 1830s, his discovery of ion conduction phenomena in solid materials (such as silver sulfide and lead fluoride) first revealed that the carriers of electric current are not limited to electrons, and ions can also migrate in the solid lattice. This laid the most original theoretical foundation for the birth of all solid-state ionics in later generations. However, throughout the 19th century and even the first half of the 20th century, due to the shallow understanding of the microscopic mechanism of ion transport in solids and the extremely low ionic conductivity of known solid ionic conductors, this field remained in the stage of exploring basic physical phenomena for a long time and failed to form a meaningful connection with practical chemical power sources. The real turning point occurred in the 1950s and 1960s. With the advancement of solid-state physics, crystal chemistry, and electrochemical testing technologies, scientists began to systematically search for fast ionic conductors with practical value. During this period, high-temperature oxygen ion conductors such as zirconia doped with calcium oxide or yttrium oxide, silver ion conductors (such as

silver iodide–silver sulfide systems), and sodium ion conductors (such as β-alumina) were successively discovered and in-depth studied [8]. They showed that in specific crystal structures, ions can achieve migration capabilities close to or even exceeding those of some liquid electrolytes. This greatly inspired the research community, proved the feasibility of developing high-performance solid electrolytes at room temperature, and gave birth to the formal establishment of "solid-state ionics" as an independent discipline. At the same time, high-temperature solid-state battery systems based on β-alumina electrolytes, such as sodium–sulfur batteries and ZEBRA batteries, were widely developed in engineering in the 1970s and 1980s due to their potential application prospects in large-scale energy storage fields. Although they were difficult to apply in consumer electronics due to their high operating temperatures (usually 300–350 °C), these practices accumulated valuable early experience for the design, packaging, and interface treatment of solid-state batteries.

Despite the progress made in high-temperature solid-state batteries, the breakthrough in lithium-ion conduction technology in solids is what truly connects solid-state battery research with today's mainstream lithium battery applications. In the 1970s, Dr. Stanley Whittingham from Exxon Corporation constructed the first rechargeable lithium–titanium disulfide battery [9]. Although its initial version still used a liquid electrolyte, it triggered a global research upsurge in lithium-based batteries and naturally inspired scientists to search for solid electrolytes that can match metallic lithium negative electrodes. The entire period from the 1980s to the 1990s was a golden age for the exploration of solid electrolyte materials. Research on the three mainstream systems—polymers, oxides, and sulfides—was launched one after another and showed different development trajectories. The pioneer of polymer electrolytes was the French Scientist Michel Armand. In the late 1970s, he systematically put forward the concept of "polymer electrolytes" and predicted that the composite of PEO and lithium salts could conduct lithium ions. The mechanism relies on the segmental movement of the amorphous region of the polymer, enabling lithium ions to migrate through continuous coordination–de-coordination with ether oxygen bonds. This pioneering work laid the foundation for flexible and easy-to-process all-solid-state batteries. However, the inherently low room-temperature ionic conductivity and narrow electrochemical window of PEO-based electrolytes have long limited their application in high-temperature or low-power scenarios. In terms of oxide electrolytes, researchers have developed from early amorphous lithium phosphorus oxynitride (LIPON) thin films and perovskite-type (such as LLTO) structures to the discovery and optimization of garnet-type (such as LLZO) structures from the late 1990s to the early 21st century. LIPON was prepared by Oak Ridge National Laboratory in the early 1990s using radio frequency sputtering. Although its bulk conductivity is not high (about 10^{-6} S cm^{-1}), it has been successfully applied in micro-thin-film solid-state batteries due to its excellent film-forming property, good interface stability with high-voltage positive electrodes, and certain ability to inhibit lithium dendrites. It still has a place in the field of microelectronics today, which proves that even solid electrolytes with moderate performance can achieve commercial application as long as the interface is stable and the process is mature. Later, garnet-type LLZO electrolytes became star materials in the

oxide system due to their high ionic conductivity (especially after being stabilized in the cubic phase) and good stability to metallic lithium [10]. The most remarkable breakthrough occurred in the field of sulfide electrolytes. Japanese scientists first discovered the thio-LISICON structure (such as Li_4GeS_4–Li_3PS_4 system) in the 1980s, but its conductivity was still not ideal. At around 2000, the team of Professor Ryoji Kanno from Tokyo Institute of Technology in Japan successively discovered argyrodite-type (such as LGPS) and its derivatives (such as Li_6PS_5Cl) with "superionic conductor" characteristics [11]. Their room-temperature ionic conductivity reached the order of 10^{-2} S cm^{-1} for the first time, which is comparable to or even better than that of liquid organic electrolytes. This milestone discovery completely subverted the traditional cognition that "the ionic conductivity of solid electrolytes must be lower than that of liquids," greatly boosted the research confidence of the entire field, and marked the formal transition of solid-state battery technology from "possible" to "feasible."

Entering the 21st century, especially after the 2010s, the driving force for the development of solid-state batteries has undergone a fundamental change. On the one hand, with the rapid increase in the requirements for energy density and safety in industries such as smartphones and electric vehicles, traditional liquid lithium-ion batteries are approaching their theoretical limits in terms of material systems (especially graphite negative electrodes), and safety accidents such as combustion and explosion caused by organic electrolytes occur frequently. As a result, the industry and investment community have turned their attention to solid-state batteries, which are regarded as the "ultimate solution." On the other hand, the accumulation of basic research over the previous decades has finally reached a critical point of qualitative change from quantitative change in material synthesis, characterization technology, and interface understanding. The research focus in this stage has gradually deepened and concentrated on a core scientific issue—the regulation of solid-solid interfaces, shifting from the initial pursuit of high ionic conductivity of the bulk solid electrolyte alone. Researchers have clearly realized that even with a bulk electrolyte with high conductivity, if the huge interface impedance and chemical/electrochemical instability problems between it and the porous positive electrode particles, as well as between it and the metallic lithium negative electrode, cannot be solved, any commitment to high performance will become empty talk in the laboratory. On the positive electrode side, the point contact between rigid solids leads to a small effective ion transport area, and positive electrode materials with high potential (>4 V vs. Li/Li^+; such as lithium cobalt oxide and high-nickel NCM) are thermodynamically unstable with most sulfide and oxide electrolytes, and side reactions will occur at the interface, forming a high-impedance interface layer. On the negative electrode side, although the infinite volume change and dendrite growth problems of metallic lithium during cycling are physically inhibited to a certain extent in the solid-state system, they have not been eradicated. Dendrites can still penetrate the electrolyte along the grain boundaries, pores of the electrolyte, or through electrochemical–mechanical coupling, leading to short circuits. These challenges have prompted global research efforts to turn to precise interface engineering: for example, by constructing an ultrathin (nanoscale) coating

layer (including $LiNbO_3$, $LiTaO_3$, LLZO, etc.) on the surface of positive electrode active particles, it can not only physically isolate direct contact with the electrolyte and inhibit side reactions but also serve as a bridge for ion transport, significantly reducing interface impedance. On the negative electrode side, strategies such as introducing a flexible polymer buffer layer, constructing an artificial SEI (ASEI) film, or using alloyed negative electrodes (such as Li–In) are explored to improve interface contact and stability. At the same time, the concept of composite electrolytes has become increasingly popular, aiming to combine electrolytes with different characteristics (such as incorporating inorganic fillers into polymer matrices or constructing polymer–inorganic multilayer structures) to achieve complementary advantages. For example, the flexibility of polymers is used to improve contact, and inorganic fillers are used to enhance ionic conductivity and mechanical modulus.

In terms of industrialization, a global competitive pattern of multi-route parallel development and a hundred flowers blooming has been formed. Japan and South Korea have obvious leading advantages in sulfide electrolytes relying on their profound accumulation in materials science and consumer electronics. Toyota Motor has invested heavily since 2010, accumulated more than 1,000 patents, and launched prototype vehicles equipped with sulfide solid-state batteries for road testing. Enterprises such as Murata Manufacturing focus on the commercialization of small polymer-based solid-state batteries. As the world's largest producer and application market of lithium-ion batteries, China has followed up on all technical routes under the dual drive of national scientific research plans and corporate venture capital, with layouts in oxide (such as LLZO), sulfide, and even polymer routes. A number of start-ups and industry–university–research cooperation platforms have emerged, and forward-looking attempts have begun in capacity planning and vehicle matching. Europe and the United States rely more on their strong basic scientific research capabilities and national-level R&D alliances, while start-ups (such as QuantumScape focusing on the oxide separator route and Solid Power focusing on the sulfide route) are promoting technological breakthroughs and have carried out close cooperation with mainstream automakers. Looking back at this history that is still being written rapidly, we can obviously see a clear path from basic scientific discovery (Faraday effect) to material system innovation (exploration of fast ionic conductors), then to focusing on core issues (interface science), and finally moving toward engineering integration and commercial verification. The development of solid-state batteries is no longer a simple laboratory technology breakthrough, but a grand system engineering involving materials science, electrochemistry, mechanics, thermal management, intelligent manufacturing, and even supply-chain reconstruction. The final barrier it faces is not only the breakthrough of a single material performance index but also the huge challenge of achieving cost control and large-scale, consistent production of the entire manufacturing chain under the premise of ensuring comprehensive performance (energy density, power density, cycle life, and safety). This history reveals to us that the next revolution in energy storage technology is likely to be nurtured in the in-depth understanding and precise regulation of the microscopic world of these solid–solid interfaces.

1.3.2 Domestic Policies on Solid-state Lithium Batteries

In November 2020, the National Development and Reform Commission issued the "New Energy Vehicle Industry Development Plan (2021–2035)," which mentioned the implementation of battery technology breakthrough action, to accelerate the solid-state power battery technology research and development and industrialization. For the first time, the research and development of solid-state batteries has risen to the national level. In addition, the national key projects have further strengthened the support for solid-state batteries. For example, among the 18 key projects released by the High-tech Department of the Ministry of Science and Technology in February 2021, there are three projects (key projects of high-end functions and smart materials, key projects of new energy vehicles, and key projects of energy storage and smart grid technology) that are closely related to solid-state batteries.

In January 2023, the Ministry of Industry and Information Technology, the Ministry of Education, the Ministry of Science and Technology, the People's Bank of China, the China Banking and Insurance Regulatory Commission, and the National Energy Administration jointly issued the "Guiding Opinions on Promoting the Development of the Energy Electronics Industry." Its core content includes "developing safe and economical new energy storage batteries, strengthening the industrialization technology research of new energy storage batteries, promoting the large-scale application of advanced energy storage technologies and products; researching and developing solid-state batteries, and strengthening the research on the standard system of solid-state batteries." It can be seen that various ministries and commissions of the state attach great importance to solid-state batteries. To implement the relevant arrangements for national scientific and technological innovation during the "14th Five-Year Plan" period, the National Key R&D Program launched the implementation of the key special project "Key Technologies and Equipment for Deep Sea and Polar Regions." In June 2023, the "2023 Project Application Guidelines for the Key Special Project of Key Technologies and Equipment for Deep Sea and Polar Regions" continued to focus on the "Ultra-High Energy Density All-Solid-State Pouch Batteries (General Key Technology Category)." It aims to break through the bottlenecks of solid-state batteries in interface construction from particles to cells under 110 MPa environment, structural evolution stress distribution, life attenuation, safety boundaries, etc., and build a disruptive ultrahigh-energy-density all-solid-state battery system to meet various deep-sea applications.

To sum up, the support of national policies will greatly promote the rapid development of solid-state lithium batteries.

1.3.3 Foreign Policies on Solid-state Lithium Batteries

Overseas countries have taken the lead in R&D and layout of all-solid-state batteries, implemented financial subsidies, and vigorously promoted technology implementation. For example, Japan has built a joint R&D system between automakers and battery factories, with government funding support exceeding 200 billion yen

(approximately 10 billion yuan), and strives to achieve the commercialization of all-solid-state batteries by 2030, with an energy density target of 500 Wh kg^{-1}. The South Korean government provides tax credits to support the R&D of solid-state batteries, and with the joint promotion of leading power battery companies, the goal is to develop commercial technology with an energy density of 400 Wh kg^{-1} by 2025–2028 and complete vehicle installation by 2030. Among the European countries, Germany has invested the most in R&D and layout. The United States is funded by the Department of Energy, with R&D led by start-ups, and has reached cooperation with many automakers, aiming to achieve an energy density of 500 Wh kg^{-1} by 2030.

1.4 Research Status and Challenges

As a new type of electrochemical energy storage system that replaces liquid electrolytes and separators with solid electrolytes, solid-state batteries, relying on their theoretically high safety and potential to break through the existing energy density bottleneck, have become the recognized next-generation power battery technology direction in the global academic and industrial circles. Their development is at a critical node from laboratory R&D to industrial-scale manufacturing. As the "soul" component of solid-state batteries, the technical maturity of solid electrolytes directly determines the commercialization process of solid-state batteries. Currently, the entire field presents a complex picture of frequent good news in basic research, in-depth advancement of engineering challenges, and accelerated competition and cooperation in industrial layout.

1.4.1 Overall Development Status of Solid-state Batteries

Under the grand narrative of global energy transformation and carbon neutrality goals, major economies have elevated solid-state battery technology to the national strategic level. In 2025, the Ministry of Industry and Information Technology of China included all-solid-state batteries in the core of new industry standard construction for the first time and began to establish a standard system. This is not only a technical specification but also a top-level design of the industrial ecosystem, aiming to set a rule framework for the global solid-state battery industry. At the same time, local governments such as Beijing and Shanghai have also included it in local industrial plans, highlighting its huge application potential in fields such as new energy vehicles, energy storage, consumer electronics, and low-altitude economy. This series of policy measures has injected strong impetus into the R&D and industrialization of solid-state batteries. In terms of market size prediction, industry data shows that the global solid-state battery market is expected to grow by more than five times in the next five years. By 2030, its proportion in China's lithium battery market is expected to reach about 10%, forming a segmented market with a scale of more than 250 billion yuan. The capital market has also responded enthusiastically. As of October 2025, the market value of leading battery companies such as

CATL has doubled, the financing amount in the solid-state battery field has surged by three times year-on-year, and leading automakers such as Tesla and BYD have signed long-term supply agreements with material suppliers, showing the market's strong confidence in technological iteration.

In terms of industrialization, a global competitive pattern of multi-technical-route parallel development and a hundred flowers blooming has been formed, and the mass production schedule has become increasingly clear. Chinese enterprises are showing a collective acceleration trend. After building the first semi-solid-state battery production line in 2024, CATL plans to realize small-batch production of all-solid-state batteries by 2026, and the energy density of its developed sulfide all-solid-state battery cells has exceeded 500 Wh kg^{-1}. The Chengdu mass production base of the Solid-State Battery Research Institute of EVE Energy was officially unveiled, and its "Longquan No. 2" all-solid-state battery successfully rolled off the production line, marking a solid step from the laboratory to industrialization. Gotion High-Tech successfully developed the vehicle-grade sulfide all-solid-state battery "Jinshi Battery" with an energy density exceeding 400 Wh kg^{-1}, and plans to start on-vehicle verification in 2025. In addition, Qingtao Energy, Funeng Technology, and other companies are also actively promoting technology implementation through material innovation or industrial chain cooperation models. From a global perspective, Toyota of Japan plans to realize on-vehicle testing of all-solid-state batteries in 2027 and large-scale mass production after 2030; Samsung SDI of South Korea is expected to start mass production in 2027; a number of American start-ups are seeking breakthroughs in energy density and charge–discharge speed. Based on the plans of all parties, 2026–2027 is regarded as a critical period for mass production and on-vehicle application, and all-solid-state batteries are expected to achieve comprehensive commercialization after 2030. Currently, the application of solid-state batteries will show a gradient characteristic. They will not replace liquid lithium-ion batteries immediately but will first be applied in scenarios with extreme requirements for performance and safety, such as high-end electric vehicles, electric vertical take-off and landing aircraft (eVTOL), humanoid robots, and aerospace. These scenarios can also bear the relatively high initial cost.

1.4.2 R&D Status of Solid-state Electrolytes

Solid electrolytes are the core of solid-state batteries, and their R&D mainly focuses on three major systems: polymers, oxides, and sulfides. Each route has its distinct advantages, disadvantages, and applicable scenarios. Polymer electrolytes, represented by PEO, have the greatest advantage of good flexibility and mature film-forming technology, and high compatibility with existing liquid battery production lines. Therefore, they are often used as a transitional solution for semi-solid-state batteries. However, their inherently low room-temperature ionic conductivity (usually $<10^{-4}$ S cm^{-1}) and narrow electrochemical window limit their application in all-solid-state and high-voltage systems. To overcome this problem, the team of Professor Qiang Zhang from Tsinghua University [12] has made a breakthrough. They successfully developed a new type of fluorine-containing polyether electrolyte

by designing a "fluoride-rich solvation structure." By introducing strong electron-withdrawing fluorine-containing groups, this electrolyte improves its resistance to high-voltage oxidation, enabling it to match 4.7 V high-voltage lithium-rich manganese-based positive electrodes. At the same time, it induces the formation of a stable interface layer rich in fluorides. The 8.96 Ah large-capacity polymer pouch all-solid-state battery assembled with this electrolyte has an energy density of up to 604 Wh kg^{-1}, and the capacity retention rate reaches 72.1% after 500 cycles at 0.5C rate. It has successfully passed the needle puncture and 120 °C hot box tests, demonstrating high safety characteristics. This achievement has pushed the performance of polymer solid-state batteries to a new height.

Oxide electrolytes, typical representatives of which are garnet-type LLZO and perovskite-type LLTO, have the greatest advantages of good chemical stability, wide electrochemical window (up to more than 5 V), and stability to air, thus having high intrinsic safety. However, they are hard in texture, resulting in poor solid–solid contact with electrodes, leading to large interface impedance. Their room-temperature ionic conductivity is usually in the order of 10^{-4}–10^{-3} S cm^{-1}, which can meet some applications but still has room for improvement. Enterprises such as Gotion High-Tech have chosen the oxide electrolyte as the core technical route and have built pilot lines. Sulfide electrolytes, such as LGPS and its derivative Li_6PS_5Cl, are currently the solid electrolyte systems with the highest ionic conductivity, reaching the order of 10^{-2} S cm^{-1} at room temperature, which is even comparable to that of liquid electrolytes. Its conduction mechanism is derived from the weak binding effect of the large radius of sulfide ions on Li^+, and the "push–pull" coordinated movement between Li^+ and the framework sulfide ions, forming a "superionic conductor" structure. This also makes it a key layout direction for giants such as CATL and Toyota in the field of power batteries. However, the fatal weakness of sulfide electrolytes is their extreme sensitivity to humidity. They react with water to produce toxic hydrogen sulfide (H_2S) gas, which puts extremely strict requirements on the production environment (such as dry room requirements) and packaging processes, directly increasing the manufacturing cost.

In addition to the above three traditional systems, the exploration of emerging electrolyte materials has never stopped. Halide electrolytes have attracted much attention in recent years. In October 2025, the team of Academician Xueliang Sun from Ningbo Oriental Institute for Advanced Materials and the team of Professor Yifei Mo from the University of Maryland, United States [13], jointly developed a new type of superionic conductor $Li_3Ta_3O_4Cl_{10}$. This material has refreshed the record of room-temperature ionic conductivity of halide-based solid electrolytes, reaching 13.7 mS cm^{-1}, and proposed a fast ion percolation network theory based on "tetrahedron-to-tetrahedron." The all-solid-state battery prepared based on this electrolyte shows excellent cycle stability under extremely low-temperature conditions of −50 °C and high room-temperature rate (3C) conditions. At the same time, the material also has significantly improved air stability, providing a new technical path for all-solid-state batteries. In addition, to take into account the advantages of different materials, the strategy of composite electrolytes has become increasingly popular. For example, inorganic fillers (oxides or sulfides) are incorporated into

polymer matrices, or polymer–inorganic multilayer structures are constructed, aiming to use the flexibility of polymers to improve interface contact and at the same time use inorganic fillers to enhance the overall ionic conductivity and mechanical modulus, achieving the effect of "combining rigidity and flexibility."

1.4.3 Core Challenges and Bottlenecks

Despite the broad prospects, the mass production of solid-state batteries, especially all-solid-state batteries, still faces a series of severe challenges. Among them, the solid–solid interface problem is generally recognized as the "Achilles' heel." The interface challenges are specifically reflected in three aspects. First is the problem of physical contact. Unlike liquid electrolytes that can perfectly wet the uneven surface of the electrode, the contact between rigid solid electrolytes and solid electrodes is mechanical point contact, resulting in a small effective contact area and a large interface impedance. During the charge–discharge process, the electrode materials (especially metallic lithium and silicon) will undergo volume expansion and contraction, which will further deteriorate the physical contact, leading to uneven local current density and even complete failure of some active materials, greatly affecting the cycle life and rate performance of the battery. Wang Fang, Chief Scientist of China Automotive Technology and Research Center Co., Ltd. [14] pointed out that the stability problem of the conductive path of high-specific-capacity positive electrode materials in a low-pressure environment has not been completely solved, which will affect the further improvement of energy density.

Second, there is the problem of interface (electro)chemical stability. Most solid electrolytes have a limited electrochemical stability window. When in direct contact with high-potential positive electrodes (such as > 4 V vs. Li/Li^+) or low-potential negative electrodes (metallic lithium, 0 V vs. Li/Li^+), thermodynamically driven decomposition reactions will occur at the interface, forming an interface phase. This interface phase plays a dual role: if it has low ionic conductivity and high electronic conductivity (such as Li_2S and Li_2O), it will become a barrier for ion transport, leading to large interface impedance and continuous consumption of active lithium, reducing the Coulomb efficiency; on the contrary, if a stable interface phase that is ion-conducting and electron-insulating (similar to an excellent SEI film in liquid batteries) can be formed through artificial regulation, it can prevent further decomposition of the electrolyte and achieve dynamic stability. The traditional solution relies on continuous external pressure application (up to 5 MPa) to maintain interface bonding, but this method significantly increases the volume, weight, and complexity of the battery system, making it difficult to meet commercial needs.

Third problem is that of lithium dendrite growth. The traditional view holds that solid electrolytes can physically block lithium dendrites, but studies have found that lithium dendrites can also grow inside solid electrolytes. The mechanisms include: growth along defects such as grain boundaries (in polycrystalline electrolytes) or cracks; electrons may penetrate into the electrolyte to reduce Li^+, forming metallic lithium deposition; during cycling, excessive local current density leads to the concentrated deposition of Li^+ at certain weak points, generating huge mechanical

stress, thereby "wedging open" the electrolyte to produce cracks, and lithium dendrites extend accordingly, eventually causing a short circuit. Wang Fang [15] also emphasized that the safety boundary of solid-state batteries is indeed wider than that of liquid batteries, but once this boundary is broken, the consequences may be more serious. This means that its safety risk characteristics are different from those of liquid batteries, requiring a brand-new evaluation system.

In addition to interface problems, the high cost is another major obstacle restricting its large-scale popularization. According to research institute reports, the unit cost of solid-state batteries is as high as 1,200 yuan $(kWh)^{-1}$, which is more than three times the cost of traditional liquid lithium-ion batteries. This is mainly due to two aspects: one is the high material cost. The solid electrolytes themselves, as well as the high-performance positive and negative electrode materials (such as lithium-rich manganese-based positive electrodes and metallic lithium negative electrodes) needed to adapt to them, are expensive. The other is the complex and immature manufacturing process. For example, sulfide electrolytes have extremely strict requirements on the production environment, requiring a full-process dry room, resulting in huge equipment investment. At the same time, the yield and efficiency of process links such as the preparation of electrodes and electrolyte films and multilayer stacking need to be improved. Although Gotion High-Tech announced that the battery yield rate of its pilot line has reached 90%, the stability and consistency control from laboratory pilot to large-scale mass production is still a huge challenge.

1.4.4 Cutting-edge Breakthroughs and Solutions

Facing severe interface challenges, the global scientific research community is constantly proposing innovative solutions. In October 2025, the team of Researcher Huang Xuejie from the Institute of Physics, Chinese Academy of Sciences [16], jointly with multiple units, published a breakthrough research result—anion regulation technology—in the international top journal *Nature Sustainability*. By introducing iodide ions into the sulfide electrolyte, this technology utilizes the interface migration characteristics of iodide ions under the action of an electric field to in situ form an LiI-rich dynamically adaptive interface (DAI) layer at the negative electrode/electrolyte interface. This interface layer can automatically fill all gaps and holes between the electrode and the electrolyte, keeping them in close contact at all times. Its mechanism of action is vividly compared to the "octopus tentacle" behavior. The test results showed that the all-solid-state battery prototype prepared based on this technology achieves stable cycling of the metallic lithium negative electrode with high areal capacity under zero external pressure or low external pressure, and the performance remains stable after hundreds of cycles. Professor Chunsheng Wang from the University of Maryland [17] commented: "This research solves the key bottleneck problem restricting the commercialization of all-solid-state batteries and takes a decisive step towards realizing their practical application." In addition, interface coating is also a widely used and effective strategy. By constructing an ultrathin (nanoscale) coating layer (such as $LiNbO_3$ and $LiTaO_3$) on the surface of positive electrode active particles, it can physically isolate direct

contact with the electrolyte, inhibit side reactions, and at the same time serve as a bridge for ion transport, significantly reducing interface impedance.

To promote the industrialization of solid-state batteries, vertical integration and collaborative innovation of the industrial chain are crucial. Qingtao Energy has adopted a unique "material + battery" bundled cooperation model, jointly building production lines with upstream and downstream enterprises in the industrial chain. This model can solve the material adaptation problem of solid-state batteries from the source. National policies also encourage automakers and battery enterprises to jointly build laboratories, promote the vertical integration of "materials–cells–systems," and provide support for the localization of core equipment such as solid-state electrolyte coating machines. In terms of standard and safety system construction, the China Society of Automotive Engineers released the "Determination Method for All-Solid-State Batteries" in May 2025, which clearly defines "all-solid-state batteries" for the first time. It requires that ion transfer be completely realized through solid electrolytes, which forms a strict technical boundary with mixed solid–liquid electrolyte batteries (often referred to as "semi-solid-state batteries"), helping to standardize the market and avoid concept speculation. At the same time, it is urgent to establish a safety standard for all-solid-state batteries. The test results in the laboratory are not equal to the actual performance of mass-produced on-vehicle batteries. A unified and strict standard is needed to ensure product reliability and consumer confidence in safety.

1.4.5 Future Development Directions

In Lux's [18] biennial market forecast report (Figure 1.2), we found that by 2035, the annual revenue of the entire energy storage market will grow to $546 billion, and the annual deployment will reach 304.6 billion kWh. By 2035, population mobility will

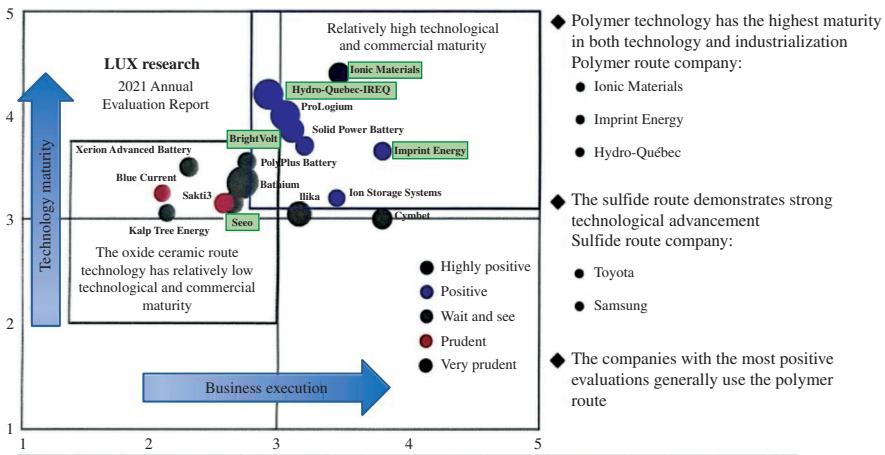

Figure 1.2 Analysis of the commercial maturity and technical advancement of solid-state electrolyte routes [7].

still be the long-term driving factor for the annual revenue and demand of energy storage, accounting for 74% of the total market share in terms of annual revenue and 91% in terms of demand. At the same time, the stationary storage market will surpass the electronic device market in 2035, and Lux expects it to become an industry worth $30.4 billion with an installed capacity of 52.5 GWh by then.

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