Proceedings of CONF-MCEE 2026 Symposium: Geomaterials and Environmental Engineering
DOI: 10.54254/2755-2721/2026.MH30748

Solid-State Electrolytes for Lithium-Ion Batteries: Mechanisms, Interfaces, Challenges, and Future Perspectives

Zekai Zhang[1*†], Qitian Chen[2†]

[1]Faculty of Engineering, Archi & Info Tech, University of Queensland, Brisbane, Australia
[2]School of Nano Science and Technology, University of Chinese Academy of Sciences, Beijing, China
**Corresponding Author. Email: 1287983854@qq.com*
[†]These authors contributed equally to this work and should be considered as co-first author.

Abstract. Solid-state electrolytes (SSEs) mark a transforming path toward high-energy-density and intrinsically safe Li-ion batteries. This review systematically summarizes the mechanisms, classifications, interfacial challenges, and industrialization prospects of SSEs. The ion transport behavior is discussed in the context of inorganic, polymeric, and composite electrolytes, focusing on the decisive role that structural factors play for Li^+ migration. The most relevant interfacial issues are specifically discussed, including chemical incompatibility, space-charge layers, and dendrite penetration, and their solution strategies, such as interface coatings, artificial SEIs, and mechanical optimization. Finally, conclusive industrial outlooks are provided by evaluating scalable synthesis, processability, and compatibility with traditional roll-to-roll manufacturing. Future directions underpin the conclusive importance of multi-ion and hybrid electrolyte systems together with sustainable recycling and integrated safety management. These synergistic advancements are expected to accelerate the transition from laboratory-scale research to industrial realization of safe, durable, and high-performance all-solid-state lithium-metal batteries.

Keywords: Interfaces, Lithium-ion batteries, Solid-state electrolytes, Stability, Transport

1. Introduction

LIBs have driven electronics, EVs and grids since Sony introduced LIBs in the 1990s. They are lightweight, of high voltage (approximately 3.6 V), energy density of 150–250 Wh/kg and cycle life of 500–800 cycles [1]. The conventional liquid electrolytes of LIBs containing LiPF6 in organic carbonates restrain their further application. For example, liquid electrolytes are flammable and can cause thermal runaway; form unstable SEI films on lithium anodes, which start lithium dendrites and short-circuits; and their electrochemical window of stability below 4.5 V precludes them from being used with high voltage cathodes [2].

Inorganic polymers and composites, and ceramics are solid-state electrolytes (SSEs) which circumvent these problems. They have flame retardancy, lithium-metal anode compatibility (maximum specific capacity is 3860 mAh/g, theoretical stoichiometry of lithium), and high-voltage

© 2026 The Authors. This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (https://creativecommons.org/licenses/by/4.0/).

DOI: 10.54254/2755-2721/2026.MH30748

cathodes in order to achieve energy density higher than 400 Wh/kg [3], as schematically illustrated in Figure 1.

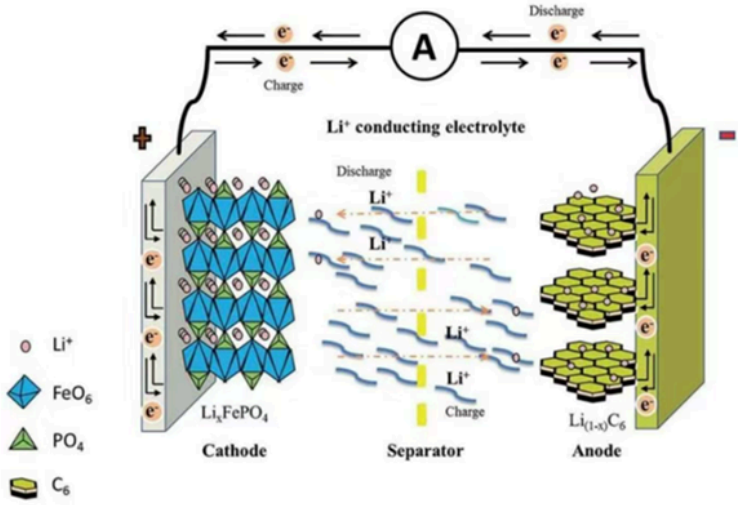

Figure 1. Schematic diagram of the internal structure of a lithium-ion battery [4]

Now, scientists focus on three categories of SSEs: inorganic SSEs with room-temperature conductivity in the range of 10^{-4}–10^{-2} S/cm but with low flexibility and humidity sensitivity; flexible polymer SSEs with a conductivity level below 10^{-5} S/cm [5]; and composite SSEs with balanced but have difficulty adjusting the dispersion of the fillers. The most important problems in SSEs are synergistic adjustment of properties, high interfacial resistance, low industrial scalability and lack of evaluation criteria.

In this review, we discuss the architecture of SSEs and their ion conduction mechanisms and review their preparation and optimization, incorporating interface engineering and summarize the history of solid-state battery development. We discuss industrial challenges, e.g., cost and scalability, and propose trends to assist researchers and professionals.

2. Ion transport mechanisms in solid-state electrolytes

2.1. Crystalline structure and migration paths of li-ions

The solid-state inorganic electrolytes with ability to transport ions is attributed primarily to the structure of the electrolytes, whose lithium-ion sites and migration channels are determined. For electrolyte $Li_7La_3Zr_2O_{12}$, its crystal network is cubic, with tetrahedral and octahedral voids connected within the crystal [6]. The lithium ion positions build up continuous three-dimensional channel, and the ion is able to diffuse in the lattice with relatively high ionic conductivity at room temperature. As shown in Fig.2, the migration path of lithium ion in garnet-type electrolyte is also cubic and the lithium ion diffuses in the crystal along certain crystallographic direction. However, lithium ion diffusion resistance in garnet-type electrolyte is low owing to the ample sulfide anion lattice, producing low resistance and migration with low activation energy [7]. For Li_3YCl_6 as electrolyte possessing $CdCl_2$-type structure, lithium ion is located between two cationic planes and ions' migration is restricted in the interlayer region. The transport of lithium ion is two-dimensional, and in most cases, it will result in low ionic conductivity because there are fewer connected channels compared to three-dimensional pathway electrolytes [8].

DOI: 10.54254/2755-2721/2026.MH30748

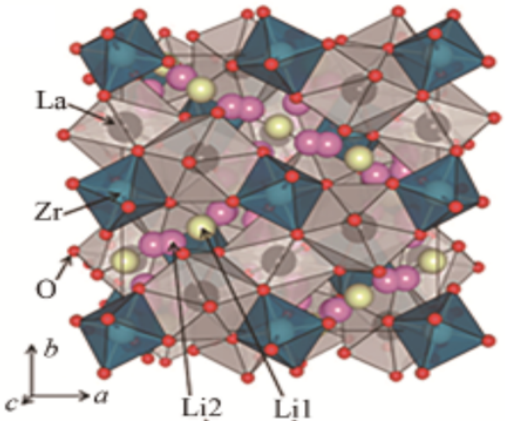

Figure 2. Schematic diagram of lithium ion migration pathways in $Li_7La_3Zr_2O_{12}$ [9]

2.2. Many interacting factors determining ionic conductivity

Many interacting factors like lattice defects, dopants and grain boundaries may influence the ion transport in high quality solid-state electrolytes, as showing in Figure 3. The lithium ion in lattice defects like lithium vacancies or interstitial lithium ions can have an alternative location to stay. By manipulating the composition of oxide electrolytes, the deviation from nonstoichiometric composition leads to lithium vacancies in the electrolyte, which can be thought of as 'channels' to support lithium ion migration. Dopant atoms regulate the crystal structure to optimize the ion migration path. For example, when gallium or aluminum is substituted with zirconium in garnet-type electrolyte, the cubic phase will be distorted and lithium ion migration channels are extended and lithium ion migration activation energy is reduced [10]. Grain boundaries are boundaries between neighboring crystals. Grain boundaries can also hinder the transport of ions. Lithium ions get concentrated at grain boundaries in polycrystalline electrolytes, where the crystal orientation gets distorted and lithium ions are in plenty. It forms a high resistance region in the crystal. This is aggravated in oxide electrolytes, which are to be sintered with caution so that the depth of grain boundaries is least [11].

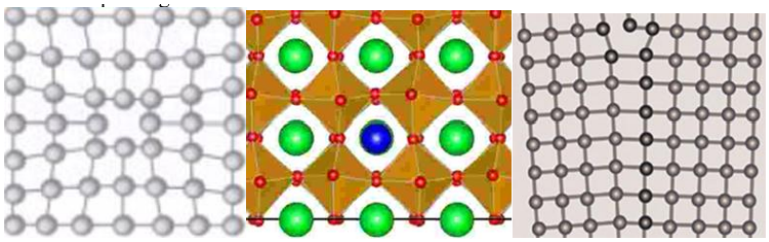

Figure 3. Schematic diagram of vacancy(left), dopant(middle) and grain boundary(right) in solid state electrolytes

2.3. Ion transport in polymers

Ion transport in solid state polymer electrolytes involves the dynamic movement of polymer segments, which is entirely different from transport in inorganic material lattice. Polyethylene oxide is far and wide the best studied polymer electrolyte. Ion transport process in polymer electrolyte has direct relation to the phase state of the polymer. As Figure 4 shows, in the crystalline region of polyethylene oxide, polymer chains are organized and in rigid state, in which lithium ion mobility is

DOI: 10.54254/2755-2721/2026.MH30748

almost forbidden. Most of the lithium ions are trapped in the coordination site of ether oxygen atom and create very low conductivity. In the amorphous region, the polymer chains are disordered and flexible. When temperature is above the glass transition temperature of polymer, the amorphous segments experience rotational and translational motions. These movements would break the coordination bonding between lithium ion and ether group oxygen atom and "carry" lithium ion to move in the polymer matrix [12]. In attempts to improve the conductivity of polymer electrolyte, people are likely to adopt copolymerization, cross-linking and other processes to increase the content of amorphous region, which would allow greater movement of polymer segments and ion transport.

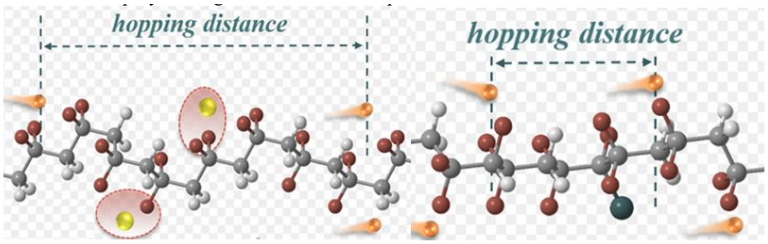

Figure 4. Lithium ion move in amorphous phase polymer (left) and in crystalline phase polymer(right) [13]

2.4. Composite electrolytes: synergetic effect

Composite solid electrolytes are made from combining inorganic fillers and polymer matrices. As shown in Figure 5, through carefully crafting synergistic effects between these two elements, the strengths of each can be optimised. The inorganic fillers, typically functioning as normal inorganic electrolytes, such as Li7La3Zr2O12(LLZO) or Li6PS5Cl, are able to deliver continuous pathways for lithium ions conduction. These pathways will avoid the polymer matrix, which has inherently low ionic conductivity and would hinder lithium ion mobility, and allow the lithium ions to move through the inorganic phase to greatly enhance the overall ionic conductivity of the electrolyte. The polymer matrix can enhance the mechanical behavior of electrode interface and electrolyte (one advantage over pure brittle inorganic electrolytes) and make the electrolyte flexible. Meanwhile, it coats on individual inorganic filler particles to prevent agglomeration of inorganic fillers and achieve a uniform composite structure. Indeed, besides the two main functional regions above, the interface region between polymer matrix and inorganic fillers is also essential in helping lithium ions transport. The interaction between the inorganic filler surface and polymer chains would disrupt the ordered polymer segment arrangement and force the amorphous part of the polymer near the interface towards the outside, with an increase in ion transport channels. The multi-channel transport process along inorganic channels, polymeric segment and interface regions make the composite solid electrolytes capable of achieving a delicate balance between good ionic conductivity, mechanical flexibility and stable electrode-electrolyte interface.

DOI: 10.54254/2755-2721/2026.MH30748

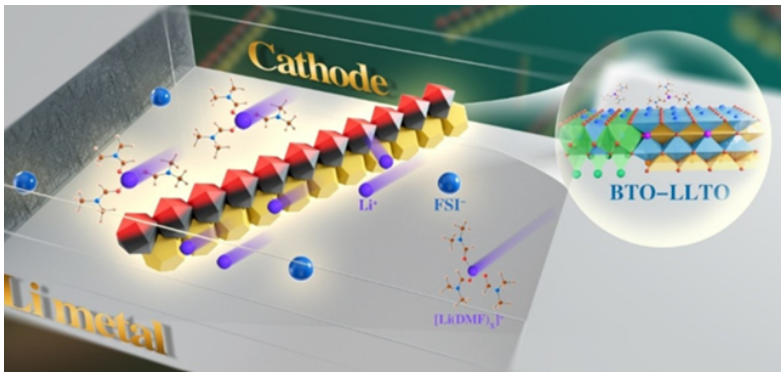

Figure 5. Schematic description of high lithium-ion conductivity composite electrolytes [14]

3. Solid-state electrolytes classification

Solid-state electrolytes (SSEs) are the material enablers of next-generation lithium-ion batteries (LIBs) and solve the issues of safety and energy density of liquid electrolytes. Their structural and chemical properties, as well as their ionic conduction behavior, can be used to divide SSEs into three broad categories: polymer solid electrolytes, inorganic solid electrolytes, and composite solid electrolytes. All the three broad categories are advantageous and have disadvantages as well, hence it is important to learn about their differences to make use of SSEs in appropriate batteries to be utilized.

3.1. Inorganic solid electrolytes

Inorganic SSEs are formed by inorganic constituents (e.g., Li, La, Zr, S, Cl, etc.) of glassy or crystalline phases, and have the properties of high ionic conductivity, stability toward lithium metal, and suppression of lithium dendrite growth. Inorganic electrolytes include three categories of subclasses: oxides, sulfides, and halides for different performance requirements.

Oxide-based inorganic electrolytes are the most extensively studied due to their excellent stability. Garnet-type oxides such as $Li_7La_3Zr_2O_{12}$ (LLZO), as shown in Fig6, possess a cubic crystal structure with interpenetrating tetrahedral and octahedral vacancies that create 3D continuous lithium diffusion channels. This unique structure enables LLZO to exhibit room-temperature ionic conductivities of 10^{-4}–10^{-3} S/cm, and it is lithium metal reaction-stable and can be applied with high-voltage cathodes in high energy density batteries [7]. High-conductivity perovskite-type oxides, such as $Li_{0.35}La_{0.55}TiO_3$(LLTO), also exhibit high conductivity but Ti^{4+} reduction at the anode interface inhibits its direct use in lithium metal cells [13]. One of the main difficulties for any oxide electrolyte is their inherent brittleness: the crystalline, hard nature of oxide electrolytes resists being processed into thin, flexible films, and a high degree of grain boundary resistance in polycrystalline samples can reduce conductivity overall (refined sintering technique to reduce grain boundaries).

DOI: 10.54254/2755-2721/2026.MH30748

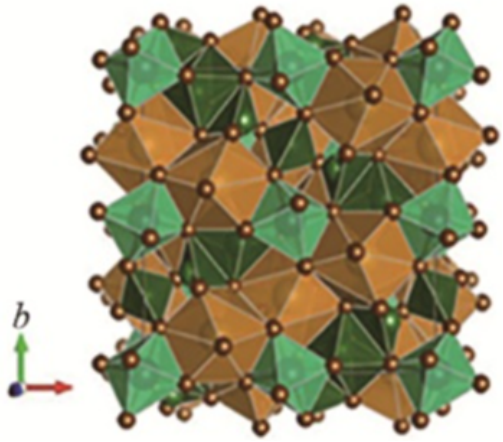

Figure 6. Schematic diagram of LLZO [9]

Because they are highly conductive at room temperature (10^{-3} to 10^{-2} S/cm, as in the case of commercial Li-ion battery using aqueous electrolyte), sulfide-based solid electrolytes get their high conductivity from their unique crystal structure that possesses large low-energy interstitial sites for Li^+ mobility [15]. Sulfides are as easily processable as brittle oxides. They can be synthesized in the form of hard films by pressing at moderate temperatures, whereas oxide materials have to be sintered at high temperatures. Sulfides also have many negative aspects. For example, they are moisture sensitive and will react with humid air by releasing very dangerous hydrogen sulfide (H_2S) gas, not only affecting the synthesis process and processing but also causing a huge risk to human health. Moreover, chemical instability relative to oxide cathodes will also cause the development of resistant interfacial layers, which would further detract from the performance of batteries following cycling.

Halide inorganic conductors are a type of solid electrolyte that has developed rapidly in recent years. Currently, they are mainly defined based on their excellent compatibility with high-voltage cathode materials. Take classic examples such as Li_3InCl_6 and Li_3YCl_6, which are part of the layered $CdCl_2$ crystal structure. In this structure, Lithium ions can only move through the two-dimensional space between layers of materials. This unique design enables the two-dimensional electrochemical stability window of these materials to reach up to 5V, making them suitable for high-voltage forms, that is, those that rely on cathodes, such as nickel-rich formulations or cobalt-free cathodes. From a practical application perspective, compared with other types of inorganic electrolytes, halides also have some advantages. Unlike brittle oxide electrolytes, they have greater mechanical flexibility. Unlike sulfides, they are not easily wetted by moisture. However, like sulfides, they still need to be assembled in a dry atmosphere to prevent hydrolysis, which limits their room-temperature ionic conductivity to approximately 10^{-4}S/cm. Compared with sulfides, this is a drawback. This value is generated due to the two-dimensional limitation of the lithium-ion transport channel.

3.2. Polymer-based solid electrolytes

Polymer-based solid electrolytes are synthesized by polymer host doped with Li salt (e.g., LiTFSI, $LiPF_6$, $LiBF_4$) and are noted for their flexibility, light weight, and surface contact with electrode surfaces. Unlike inorganic SSEs that function on the basis of lattice channels for ion transportation, polymer electrolytes support Li^+ conduction through polymer segment dynamic motion, and their conductivity is greatly dominated by the phase state and chemical structure of the polymer.

DOI: 10.54254/2755-2721/2026.MH30748

The best-studied polymer matrix is poly(ethylene oxide)(PEO), a linear polymer whose repeat ether oxygen (-O-CH_2-CH_2-) groups coordinate Li^+ ions [16]. In pure PEO, Li^+ ions are in the form of complexes where the ion is coordinated to polymer ether oxygen atoms, and ion conduction arises when polymer segments display rotational and/or translational motion ("segmental motion") to break and re-form these complexes. PEO has the advantages of low cost, simplicity of preparation, and castability into thin, flexible films characteristics desirable for large-scale batteries. Nonetheless, PEO is very crystalline at ambient temperature: the rigid crystalline arrangement of the polymer hinders the segmental motion, leading to very low ionic conductivity ($<10^{-6}$ S/cm) at ambient temperature [17]. To overcome this, methods such as cross-linking (prohibiting the growth of crystals), blending with plasticizers such as succinonitrile or ethylene carbonate (to increase amorphous content), or copolymerizing PEO with a different monomer, such as polypropylene oxide (another polymer), to minimize crystallinity. These approaches are demonstrated in Figure 7. These are sufficient to increase the conductivity to 10^{-5}–10^{-4} S/cm at room temperature, still far lower than inorganic SSEs.

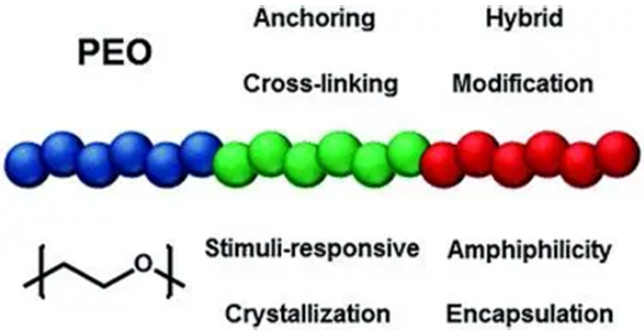

Figure 7. Schematic diagram of PEO [17]

With the built-in disadvantage of poly (ethylene oxide)11(PEO), other arrays of additional polymer matrix materials have been synthesized for use in solid electrolyte composites. Polycarbonates such as poly (ethylene carbonate)12(PEC) and poly (propylene carbonate)13(PPC) possess higher dielectric constants than PEO, a feature that facilitates lithium salt dissociation and inhibits ion-pairing with a net composite effect of promoting ionic conductivity. More broadly, they possess broader electrochemical windows than PEO, which are limited to ~3.8 V by oxidative degradation at high voltage. Polyacrylates like poly (methyl methacrylate)14(PMMA) provide a useful alternative too: their rigid polymer backbones inhibit crystallinity (a general inhibition to ion movement in polymers), and their carbonyl groups promote coordination-mediated Li^+ ion mobility. Ionic liquid-based polymers, or "poly (ionic liquids)" constitute a newer family that combines the satisfactory ionic conductivity of the ionic liquids with the mechanical rigidity of solid polymers. They have good thermal stability in combination with wide electrochemical windows, and importantly, their costs of production are appreciably lower than in the case of the conventional PEO-based electrolyte formulations.

Remarkably, one universal polymer electrolyte weak point across all compositions is loss of mechanical strength at high temperature. With an increase in temperature, polymer segments are more mobile—improving ionic conductivity—but the polymer matrix is softer, which threatens the penetration of lithium dendrites and compromises the integrity of the battery. In addition, compatibility with high-voltage cathodes is poorer than with inert solid-state electrolytes (SSEs), and this is a limitation that hinders their use in high-energy-density battery systems.

DOI: 10.54254/2755-2721/2026.MH30748

3.3. Composite solid electrolytes

Composite solid electrolytes (CSEs) are designed to capture the benefits of polymer-based solid-state electrolytes (SSEs) without inheriting their respective weaknesses. A polymer matrix with infused inorganic filler particles, their performance is dependent upon synergistic interactions between these two phases—interactions enabling a compromise of ionic conductivity, mechanical flexibility, and electrochemical stability.

The most significant advantage of CSEs is their multi-path transport of Li^+: inorganic filler particles are conductive bridges throughout the whole polymer matrix to form fast Li^+ migration channels which avoid going through the polymer phase (which is not conductive by itself). For example, LLZO-PEO composites achieved 10^{-4}–10^{-3} S/cm of room-temperature ionic conductivities, one order higher than that of pristine PEO. In the composite systems of LLZO-PEO, Li^+ can go through the lattice of LLZO particles or diffuse along the particle-polymer interface (where the ordered crystallinity of the polymer is damaged) [18]. The Li^+ transport pathways and the interfacial structure in LLZO–PEO composites are well-demonstrated Figure 8. Even though inorganic SSEs have the problem of brittleness: the polymer matrix solves this problem by covering the whole filler particles with a soft film that is tightly in contact with the electrode during charge-discharge processes. The inherent softness of the polymer also allows for simpler processing of CSEs into thin films in industrial manufacturing—no high-temperature sintering process (required for inorganic electrolytes) is required for battery assembly with the use of CSEs.

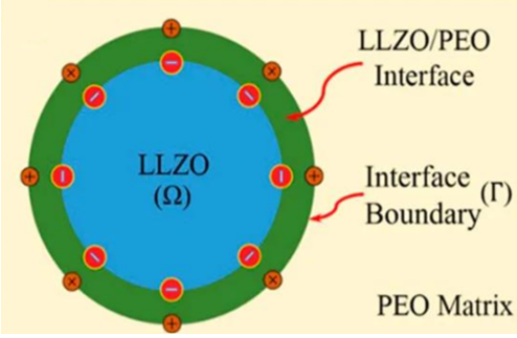

Figure 8. Schematic diagram of LLZO-PEO composites solid electrolytes [19]

To further promote the performance of CSEs, researchers adopt advanced hybrid design strategies. The nanoscale fillers are more favorable than microscale fillers because they possess much greater specific surface areas and create more filler-polymer interface areas for Li^+ to travel across these interfaces. Surface treatment is yet another major route to optimize the performance of CSEs: if silane coupling agents treat LLZO particles, they can chemically interact better with hydrophobic polymers like PEO and agglomeration of such fillers is reduced. Simultaneously, filler aggregation is decreased by reducing the interfacial contact resistance. Core-shell structured fillers, for instance, LLZO@Al_2O_3 or Li_6PS_5Cl@SiO_2, are also utilized to coat the surface of fillers with inorganic shells: these shells can act as a barrier to prevent direct contact between reactive fillers (e.g., sulfides) and lithium metal. The core part of core-shell structured fillers is still able to provide high Li^+ conductivity [20].

There are still many challenges to the commercialization of CSEs. For example, it is hard to disperse the fillers uniformly at high loadings (in general >20wt%): the filler particles with agglomerates will form cavities in the whole matrix, which increase the interfacial resistance and reduce the mechanical stability of the composite solid electrolyte. The inorganic filler's grain

DOI: 10.54254/2755-2721/2026.MH30748

boundary resistance continues to exist: although nanoscale particles are used, they still have small grain boundaries which can affect the Li^+ transport process. It is also more difficult to control the dispersion of the filler and the thickness of the film during large-scale manufacturing of CSEs, compared to pure polymers or inorganic powders [21]. It is only by breaking these hurdles that we can harness the potential of CSEs as a "universal" electrolyte for any commercial solid-state LIBs.

4. Interface challenges and engineering strategies

4.1. Solid electrolyte/electrode interfacial compatibility

The interface between solid electrolytes and electrodes plays a decisive role in determining the performance, stability, and lifespan of solid-state lithium batteries. However, interfacial incompatibility is one of the most critical challenges. Chemical potential mismatches, mechanical stiffness differences as well as the formation of unstable interfaces can cause serious degradation issues such as the creation of voids, cracks, dendrite penetration, and the progressive development of interfaces, greatly increasing interfacial resistance and capacity degradation [22]. In specific electrolyte materials involving sulfides and oxide electrolytes, strong reactions can occur between the lithium or silicon electrodes and the electrolyte components to form compounds such as Li_2S, Li_3P, and Li_2O that hamper ionic conduction or create fragile solid electrolyte interfaces [23]. On the other hand, the electrochemical degradation of electrolyte materials at high voltages leads to the development of interfacial resistances at the electrodes [24].

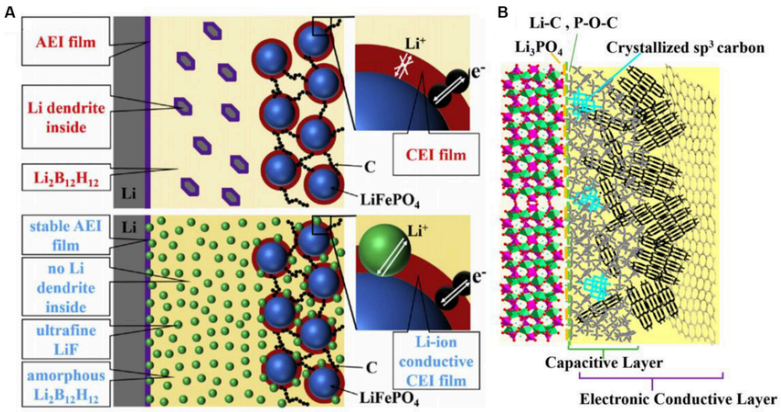

Figure 9. Schematic illustration of electrode-electrolyte interface structure [25]

In order to tackle the above challenges, many interfacial engineering techniques have been proposed. Physical interfacial barriers such as coating and buffer layers can decouple the reactive interfaces and remain elastic at the same time. This can be achieved by composite interfaces that can couple polymers or ionic liquids optimistically to withstand the stress. On the other hand, chemical interfacial modification involving doping and atomic reconstruction at the interface can optimize the interfacial structure. Furthermore, self-healing interfacial designs have been proposed to dynamically stabilize the interface during the cycling process. All of the above techniques aim to create a dynamically conductive ionic interface but electronically nonconductive at the same time. This interface should ensure a homogenous flow of the Li^+ ions and inhibit the formation of dendrites [26]. Figure 9 presents the interface degradation mechanism and its corresponding mitigation strategies, providing a comprehensive visualization framework for interface optimization in solid-state batteries.

DOI: 10.54254/2755-2721/2026.MH30748

4.2. Issues of interfacial resistance and space-charge layers

The important physicochemical issues contributing to the interfacial resistance in all-solid-state lithium batteries (ASSLBs). The high interfacial resistance between the solid electrolyte (SSE) and electrodes arises due to several factors: chemical incompatibility, the effect of electronic leakages in the SSEs, the space charge layer (SCL), and the instability due to the contact of the SSEs with the metal lithium [27]. In the case of chemical incompatibility between the electrodes and the SSEs, the chemical reactions at the interfaces form unstable interfacial materials that lead to the consumption of the available lithium and the destruction of the ionic paths. This results in a loss of ionic conductivity. On the other hand, the leakages of electrons in the solid electrolytes cause self-decomposition reactions between the electrolyte components. This forms electroconductive materials like Li_2S or Li_3P [28].

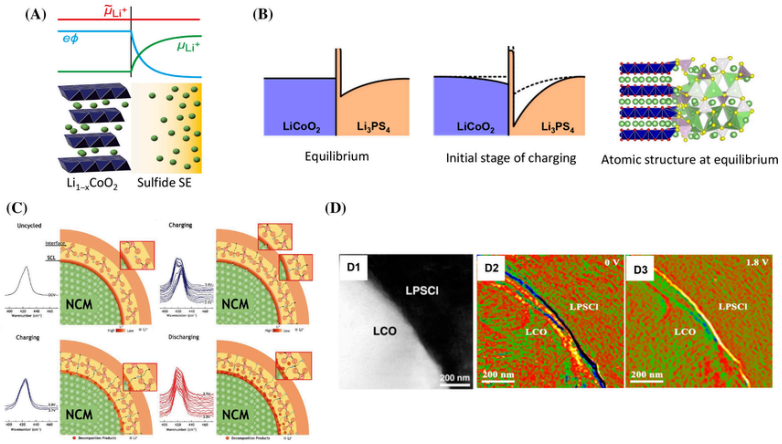

Figure 10. Formation mechanism of the space-charge layer (SCL) at the solid electrolyte/electrode interface [29]

The dominant factor in the interfacial resistance is attributed to the space charge layer (SCL), which forms due to the potential barrier at the SSE/electrode interface and the matching of Fermi levels [30]. As evident from Figure 10, the SCL results in the depletion or buildup of lithium ions in localized areas. This affects the concentration of ions as well as the electrical field at the interface. As a result, the interfacial resistance between the electrodes gets substantially enhanced. In oxide or sulfide electrolytes, the SCL can extend up to a few nanometers. This creates a barrier to the flow of lithium ions. This further slows down the kinetics of the interfacial reactions. Moreover, the lack of contact between the metallic lithium electrodes and the SSE can create hotspots. This can accelerate electrochemical irreversibility and the formation of lithium dendrites. When the lithium dendrites grow through the SSE, the entire solid-state battery can get short-circuited due to the generation of multiple pathways for the flow of electrons. In order to counter such issues, interfacial engineering has to tackle both ionic and electronic transport. This can be achieved through techniques like matching chemical potential, creation of hetero-structural interfaces, and doping. Such procedures can eliminate the effects of SCL. Proper optimization of electrode/electrolyte matching can reduce interfacial resistance.

4.3. Chemical/electrochemical stability against Li metal anodes

The lithium-sulfide solid electrolyte (SE) interface represents one of the most chemically unstable interfaces in all-solid-state batteries. The highly reducing property of lithium metal favours the

DOI: 10.54254/2755-2721/2026.MH30748

occurrence of spontaneous redox reactions between lithium metal and the sulfide solid electrolytes like Li_6PS_5Cl and $Li_{10}GeP_2S_{12}$. As a consequence, the corresponding decomposition products like Li_2S, Li_3P, and LiCl form. These compounds can develop a so-called mixed conducting interphase (MCI), whose ionic as well as electronic conductivities strongly facilitate the ongoing side reactions at the interface between the lithium metal and the SE [31]. In contrast to this, the interfacial resistance will significantly increase during cycling because of the consumption of lithium and the development of voids. In addition to this, the risk of dendrite formation will increase. Moreover, the reactions mentioned above are thermodynamically preferred because of the limited electrochemical window of the sulfide solid electrolytes. Therefore, improving the interfacial compatibility through artificial SEIs, buffer coatings, or interface engineering has become a critical step toward achieving stable and long-life Li metal all-solid-state batteries.

4.4. Strategies to improve interfacial stability

To address the severe chemical and electrochemical instabilities between Li metal and solid electrolytes (SEs), extensive interface-engineering strategies have been developed to mitigate redox reactions, suppress decomposition, and maintain stable Li^+ transport pathways. These approaches focus on thermodynamic stabilization, artificial interphase formation, and mechanical optimization.

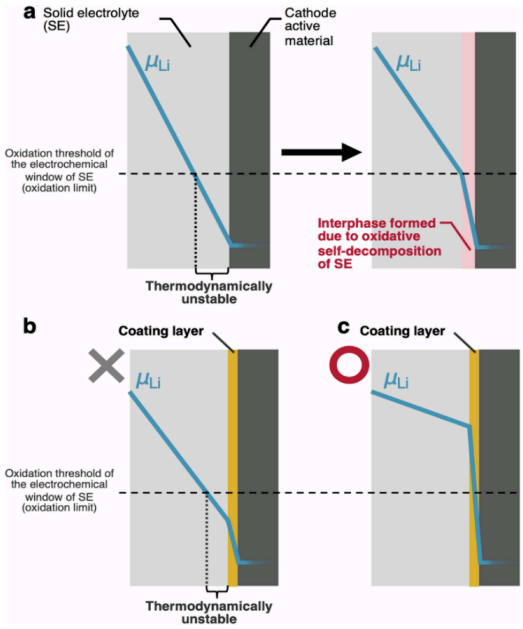

Figure 11. Schematic illustration of interfacial stability with (a) uncoated, (b) improperly coated, and (c) optimized coated interfaces [32]

4.4.1. Interfacial coatings and buffer layers

Figure 11 schematically illustrate the thermodynamic origins of interfacial instability and the effect of coating layers [32] In Figure 11a, when the SE directly contacts the electrode, the Li chemical potential (μLi) crosses the oxidation threshold, leading to spontaneous oxidative decomposition and the formation of a high-impedance, unstable interphase. As shown in Figure 11b, the presence of an improper coating fails to confine μLi within the stability window, and side reactions persist. By contrast, Figure 11c demonstrates that an optimized coating—for instance $LiNbO_3$, Li_2ZrO_3 or Al_2O_3—can successfully align μLi within the electrochemical stability window. This prevents self-

DOI: 10.54254/2755-2721/2026.MH30748

decomposition of the SE, reduces interfacial resistance, and enhances cycling stability. Proper coating design thermodynamically stabilizes the interface by adjusting μLi gradients and minimizing electron leakage. Coating and buffer-layer strategies are central to interface engineering in sulfide-based all-solid-state systems [33].

4.4.2. Artificial SEI formation

Apart from the external coatings, the creation of the Artificial Solid Electrolyte Interphase (Artificial SEI) also serves as another effective strategy in improving the lithium/solid electrolyte interface. This can typically refer to the ion-conducting and electronically insulating layer that can protect the lithium metal from the electrolyte to avoid any reactions. This can consist of materials like Li_3PO_4, LiF, and Li_3N.

Recent studies have proved that the use of multi-component inorganic composites as artificial interfaces can greatly improve the wettability and long-term interfacial stability. For instance, the scheme proposed by Ji et al. in 2024 used a composite artificial interface to create a layer of LiF and Li_2O on the surface of the thin Li anode (~ 7.5μm thick), thereby allowing the stable contact of the LLZO type of garnet electrolyte [34]. The results proved that their solid-state battery exhibited a stable overpotential and prevented the penetration of dendrites for hundreds of hours. Henceforth, the dual approach involving the use of solid SEI interfaces and coating techniques can greatly improve the interfacial stability at both chemical and mechanical interfaces. This approach can play a pivotal role in the development of solid-state lithium metal batteries.

4.4.3. Mechanical/structural optimization

Besides the chemical stabilization effect, the optimization of the solid/solid interface through mechanics and structure is vital. In the processes of both Lixelectrodes' deposition and stripping, the accumulated stress and delamination of the interface can cause the generation of voids and the development of dendrites. The use of elastic interlayers or gradients can reduce stress effects and ensure strong ionic binding between the Lixelectrodes and the solid electrolyte. In addition, the effect of applying the appropriate pressing force and enhancing electrolyte densification can efficiently inhibit the generation of interfacial voids and promote homogeneous Lixelectrode deposition.

5. Industrialization challenges and practical solutions

5.1. Scalable synthesis method

SSE scalable fabrication has been a significant obstacle to the industrialization of all-solid-state batteries. In the context of scaling up SSEs, as shown in Figure 12, the existing forming methods including screen printing, calendaring, and sintering are found to have some advantages in laboratory-scale densification.

DOI: 10.54254/2755-2721/2026.MH30748

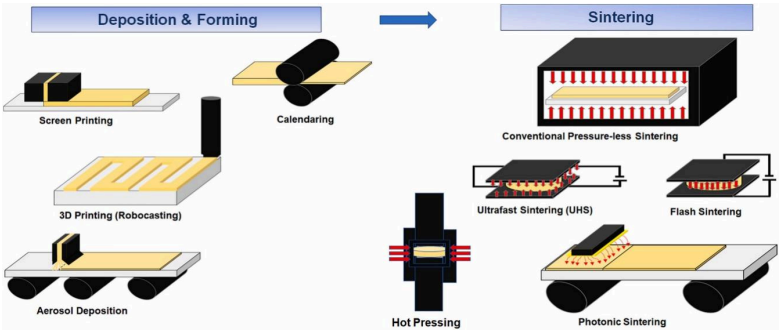

Figure 12. Solid-state battery manufacturing process diagram [35]

Thin-film deposition techniques like sputtering, pulsed laser deposition, and atomic layer deposition can be used to create high-quality thin films of LiPON and LLZO. However, the cost and lack of scalability of these techniques make them less desirable. In the case of sulfide electrolytes, other limitations like the requirement to be processed in the inert atmosphere due to their reactivity add to the cost and complexity [35].

Solution-based synthesis provides a more scalable option. Slurries and sol-gel methods can easily produce coatings that can be scaled up for roll-to-roll processes. However, issues like lithium loss, optimization of the binder, and phase purity during the drying stage remain. Although aqueous methods are safer and more cost-effective, degradation of the oxide or sulfide electrolyte can occur.

To achieve scalable manufacturing, the future development should aim at continuous coating and low-temperature sintering. This will enable the replacement of the current deposition process. Some of the techniques required in the development of SSEs include optimization of the ionic conductivity and the mechanical properties. This can be achieved through the optimization of the packaging of the powders and the binder dispersion.

5.2. Processability and mechanical properties (flexibility, densification)

Mechanical and processing requirements of solid electrolytes have been shown to play an important role in the reliability and scalability of all-solid-state batteries. Inorganic electrolytes like oxides and sulfides have high ionic conductivity. However, their main weaknesses are brittleness and lack of flexibility. This can cause delamination during the cycling process. Figure 13 shows how the stress accumulated at the interface between the Li and electrolyte causes spallation and the development of pores.

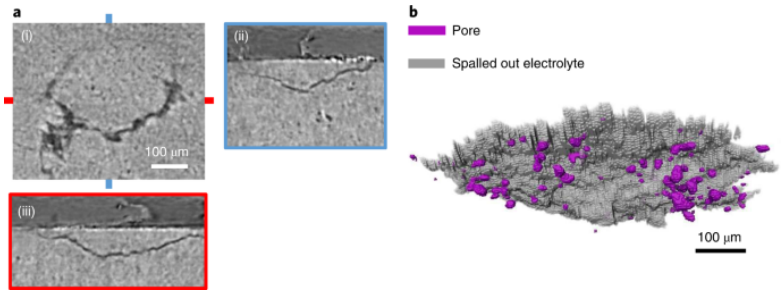

Figure 13. Visualization of plating-induced cracking in solid electrolytes [36]

The challenge here lies in accomplishing both densification and flexibility. While high-temperature sintering enables neck formation between the particles and thereby minimizes the

DOI: 10.54254/2755-2721/2026.MH30748

porosity, thereby improving ionic conductivity, overly dense thin films tend to generate stress and thereby can rupture under cycling. On the other hand, less dense thin films can preserve pores that can improve filament penetration of the lithium.

Recent studies have highlighted advanced densification methods to overcome these trade-offs. Ultrafast, rapid-induction, and cold sintering techniques allow for high relative densities while maintaining low thermal stress and energy consumption, showing feasible processes for mechanically stable solid electrolytes [37]. In addition, the use of polymer–ceramic composite electrolytes have proven to enhance flexibility and tolerate mechanical deformation at no sacrifice in ionic conductivity. These strategies together provide feasible routes to large-area manufacture of robust, flexible solid electrolytes toward industrial manufacturing of solid-state batteries.

5.3. Compatibility with existing battery manufacturing processes

The compatibility between the solid electrolyte fabrication and the lithium-ion production lines is crucial to the industrial application of solid-state batteries. These conventional solid electrolytes require high-temperature sintering or vacuum-based deposition that is challenging to be integrated into the current roll-to-roll coating, calendaring, and lamination processes of Li-ion cells. This incompatibility has resulted in increased manufacturing cost, equipment modification, and complexity in the process, hindering the large-scale commercialization of solid-state batteries.

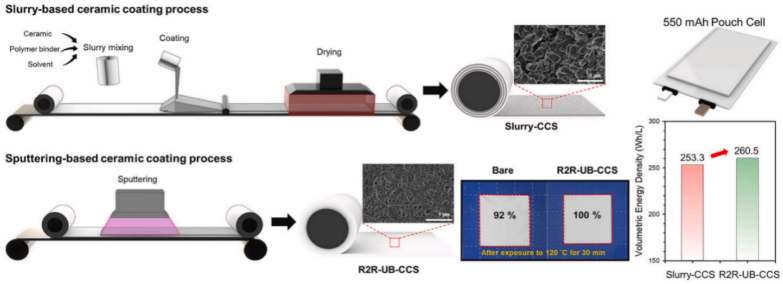

Figure 14. Solid-state electrolyte roll-to-roll coating diagram [38]

Observation from Figure 14 suggests that the roll-to-roll coating process represents a practical route toward achieving such manufacturability compatibility. In slurry-based ceramic coating, ceramic powders, polymer binders, and solvents are mixed into a homogeneous slurry that can be continuously coated and dried into flexible solid electrolyte films. The process is very much analogous to existing electrode slurry coating techniques, which can share the same large-format drying and calendering equipment. As a parallel approach, the sputtering-based coating technique offers a solvent-free alternative that can deposit dense and uniform films at relatively low temperature. Both techniques have demonstrated the feasibility of integrating the manufacturing process for solid electrolytes into the current Li-ion assembly lines without redesigning extensive equipment.

There are a number of industrial advantages provided by such compatibility. Continuous roll-to-roll processing can enable mass production, enhance the uniformity of the films, and decrease the energy and labor costs-issues largely responsible for scalability barriers in solid-state electrolytes. In addition, low-temperature and solvent-controlled environments provide better assurance of operational safety by avoiding risk due to volatile precursors and preventing any degradation of sulfide systems by moisture. Together, these manufacturing innovations put in place an industrial pathway toward solid-state battery production in existing infrastructure.

DOI: 10.54254/2755-2721/2026.MH30748

5.4. Cost and raw material availability

The cost and availability of the raw materials are the critical challenges that restrict the large-scale commercialization of solid-state batteries. Traditional oxide or sulfide electrolytes commonly depend on expensive precursors, usually with very high purity, such as $Li_7La_3Zr_2O_{12}$ (LLZO) or $Li_{10}GeP_2S_{12}$ (LGPS), which require complicated synthesis conditions. Furthermore, the essential processes of high-temperature sintering and vacuum deposition associated with these materials greatly increase energy consumption and production cost, acting as a significant barrier to mass manufacture.

The introduction of polymer–ceramic composite electrolytes open up promising routes to reduce material cost while maintaining adequate electrochemical performance. In such a configuration, cost-effective polymers, including polyethylene oxide, are combined with ceramic fillers in hybrid solid electrolytes. Figure 15 illustrates three structural configurations: (a) ceramic-in-polymer, with ceramics acting as fillers in a flexible polymer matrix; (b) intermediate, with a balanced distribution of both phases; and (c) polymer-in-ceramic, with a continuous ceramic framework that ensures ionic conduction. These structures allow for a trade-off between cost, mechanical flexibility, and ionic conductivity.

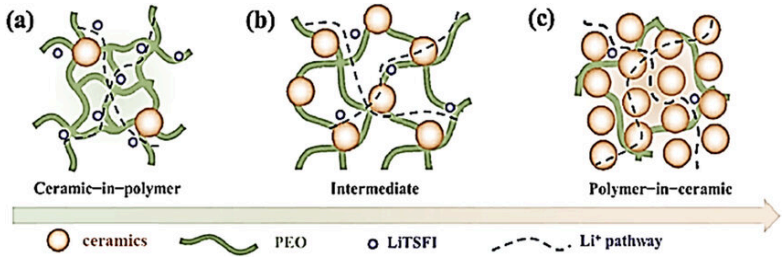

Figure 15. Schematic diagram of polymer–ceramic composite electrolytes [39]

Composite systems drastically reduce reliance on rare elements, such as germanium and lanthanum, compared to their fully inorganic solid electrolyte counterparts. The use of polymers further allows for low-temperature or solvent-based processing, reducing raw material waste and energy needs. Moreover, tunability of polymer-ceramic ratios enables process optimization within a wide range of different manufacturing conditions toward scalability and economic viability.

The combination of inexpensive polymers and moderate-temperature processing thus presents a viable pathway to large-scale manufacturing of solid electrolytes. Such materials not only reduce manufacturing costs but also enable flexible, roll-to-roll fabrication compatible with the existing Li-ion production infrastructure. In this regard, the development of hybrid electrolytes effectively bridges the gap between high-performance but costly inorganic systems and processable, low-cost polymeric systems, thereby enabling practical industrialization of solid-state batteries.

5.5. Safety considerations in industrial applications

In the industrialization process of solid-state batteries, safety is the most basic prerequisite, especially in sulfide-based systems, which are highly restrained by the sensitivity of the SE material and process complexity. Sulfide electrolytes have super-high sensitivity to air and moisture; thus, manufacturing and assembly need to be processed under an inert atmosphere with a dew point lower than –40 °C to avoid decomposition. In order to ensure good interfacial contact between the electrode and electrolyte, there is usually externally applied pressure of around 30 MPa. However,

DOI: 10.54254/2755-2721/2026.MH30748

too high a stacking pressure might lead to mechanical distortion and safety hazards. It is therefore of great importance to develop low- or zero-pressure cycling sulfide-based ASSBs for both safety and scalable manufacturing [40].

Although solid electrolytes themselves are non-flammable at a cell level, interfacial resistance in cycling may cause localized heating. Other major risks pertain to batteries with lithium metal anodes: dendrite penetration. Interface engineering-that is, the attainment of low-impedance and mechanically stable contact structures-reduces the risk of short circuits and thermal runaway. Strict quality control and FMEA will be indispensable for preventing localized failures from propagating and ensuring safe and sustainable ASSB manufacturing.

6. Future perspectives

6.1. Advanced interface and multi-ion electrolyte design

Designing advanced interfaces and multi-ion solid electrolytes are crucial directions toward the development of next-generation all-solid-state batteries. Conventional single-ion electrolytes, for example, those relying solely on Li^+ conduction, usually suffer from drawbacks due to interfacial polarization, space-charge accumulation, or poor compatibility with high-voltage electrodes. In contrast, multi-ion systems introduce additional cations to co-participate in charge transfer, which leads to enhanced ionic mobility and improves the electrochemical stability at the electrode–electrolyte interfaces. As illustrated in Figure 16, different multi-ion configurations can generate various ion transport pathways and co-intercalation mechanisms. These configurations can effectively balance the charge distribution, reduce the diffusion barrier, and inhibit dendrite growth in repeated cycles [41].

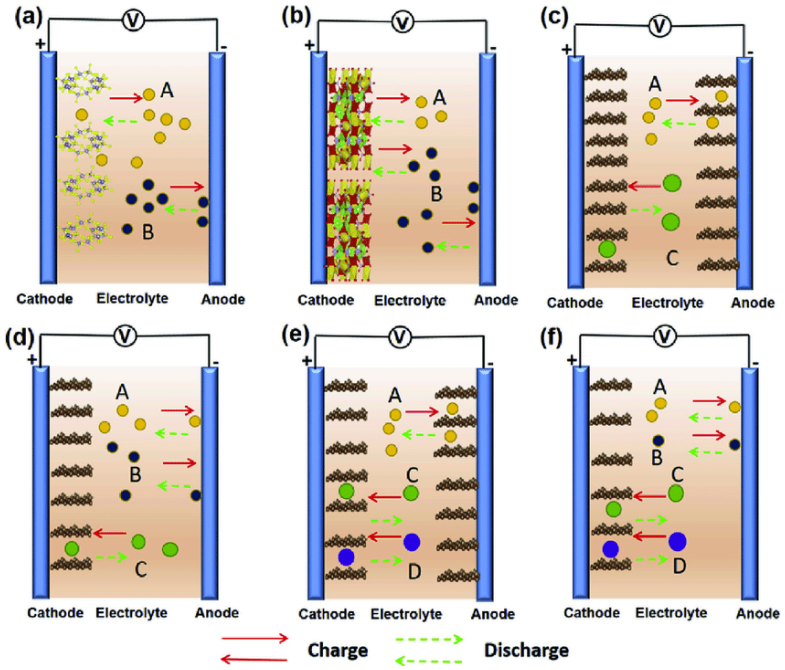

Figure 16. Schematic of typical rechargeable batteries based on different multi-ion configurations [41]

In addition, hybrid solid electrolytes that integrate the sulfide, oxide, and polymer phases can further synergistically combine high ionic conductivity with mechanical and chemical stability.

DOI: 10.54254/2755-2721/2026.MH30748

Sulfide components provide fast Li^+ transport, while oxide and polymer networks enhance interfacial adhesion and structural robustness. Chemical tailoring of interfacial layers or the introduction of artificial buffer phases represents further strategies toward mitigating interfacial impedance for improved long-term cycling performance under high current densities. Such engineered interfaces enable uniform Li deposition and enhanced reversibility in solid-state cells.

Furthermore, the in-situ and operando characterization techniques, including X-ray absorption spectroscopy, Raman spectroscopy, and neutron diffraction, will play a crucial role in real-time monitoring of interfacial evolution. These techniques have enabled direct observation of ion migration, interphase formation, and degradation mechanisms, thus providing important insights into the rational design of next-generation electrolytes. Overall, multi-ion and hybrid solid electrolytes present a practical route to accomplish high energy density, improved safety, and enhanced durability of advanced all-solid-state lithium-metal batteries.

6.2. Industrialization strategies: recycling and safety management

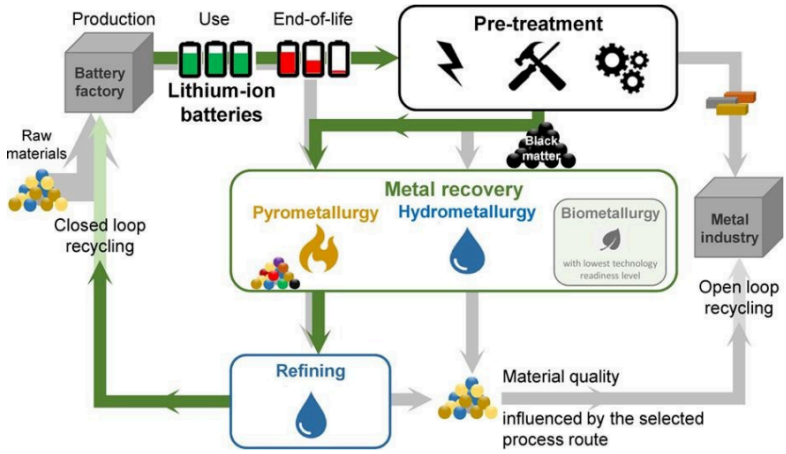

Figure 17. Battery materials recycling flow chart [42]

Industrialization of all-solid-state batteries needs not only material innovations but also sustainable and safe manufacturing strategies. Efficient recycling and effective thermal management, in view of life cycles, are two key strong pillars for large-scale deployment. Figure 17 illustrates that closed-loop recycling processes can recover valuable metals from end-of-life lithium-ion or solid-state batteries via pyrometallurgical, hydrometallurgical, and biomining routes. Among these, pyrometallurgy offers robust scalability, while hydrometallurgy provides higher metal recovery efficiency with reduced energy consumption. Biomining, though at a low technology readiness level, presents an environmentally friendly alternative for future circular manufacturing [42]. This reintegration of recovered materials into new production cycles makes recycling not only minimize resource depletion and waste generation but also lower the overall production costs, enhancing economic and environmental sustainability.

Besides, operational safety is one of the keys to solid-state battery commercialization. Figure 18 shows that advanced battery thermal management systems, including heat pipe, liquid cooling, phase-change materials, and refrigerant-based systems, are designed to avoid overheating and fire risks of batteries. They can keep temperature uniformity within battery packs well and avoid local hot spots that could eventually cause a thermal runaway. Hybrid configurations coupling air or liquid cooling with heat pipes offer enhanced heat dissipation efficiency and reliability, especially under high-power operation [43].

DOI: 10.54254/2755-2721/2026.MH30748

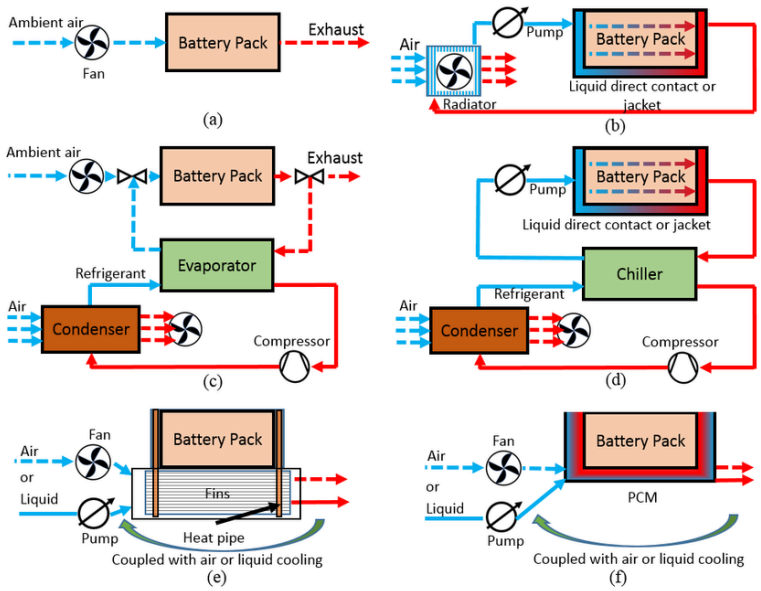

Figure 18. Battery thermal management methods diagram [43]

The integration of circular recycling processes with advanced thermal management technologies contributes to the industry's twin goals of sustainability and safety. These industrial strategies are very important and fill the gaps from laboratory-scale innovation to large-scale commercialization, opening routes toward a sustainable ecosystem of solid-state batteries that could meet global energy and environmental challenges.

6.3. Integration towards safe all-solid-state lithium-metal batteries

Successful implementation of ASSLBs calls for balanced material innovation, sustainable manufacturing, and safety assurance. Advances in multi-ion and hybrid electrolyte design have overcome important interfacial challenges, while circular recycling systems and optimized thermal management ensure long-term reliability and environmental responsibility. Next-generation development should entail harmonization of these technological pillars into a unified production framework that demonstrates the capability of large-scale, cost-effective deployment.

A fully integrated ASSLB ecosystem should move toward a "design–manufacture–recycle" loop, where safe material synthesis, standardized cell fabrication, and efficient recovery processes coexist. Safety standards, quality control systems, and end-of-life management protocols must be developed in collaboration among research institutions, industries, and policy makers. Besides, digital-driven manufacturing technologies can further enhance scalability and process precision.

It enables the all-solid-state lithium-metal battery to transition from laboratory-scale demonstrations to real-world applications for electric vehicles and grid-scale storage by incorporating advanced interface engineering, sustainable industrialization, and resilient system design. This will represent a holistic integration toward a much safer, greener, and more efficient energy future.

7. Conclusion

This review seeks to systematically synthesize the essential mechanisms, classification, interfacial challenges, industrialization bottlenecks, and future directions of solid-state electrolytes for

DOI: 10.54254/2755-2721/2026.MH30748

advanced LIB applications. SSEs address the intrinsic limitations of conventional liquid electrolytes, including flammability-induced thermal runaway, lithium dendrite nucleation, and narrow electrochemical stability windows; therefore, they are a key material platform in enhancing LIB safety, energy density (>400 Wh/kg), and cycle life, essential to electric vehicle and grid-scale energy storage.

Ion transport behaviors of SSEs are then categorized by material type: inorganic SSEs rely on crystalline lattice channels for Li^+ migration, such as 3D pathways in cubic LLZO and 2D interlayers in $CdCl_2$-type halides; polymer SSEs depend on the segmental motion in amorphous regions, such as for PEO-based systems; composite SSEs achieve synergistic performance through multi-path transport, including inorganic channels, polymer segments, and filler-polymer interfaces, by overcoming single-component trade-offs.

Interface engineering, such as by protective coatings, artificial SEIs, and mechanical optimization, reduces high interfacial resistance caused by chemical mismatch and space-charge layers. Solutions to industrialization barriers include scalable synthesis, processability, and cost, possibly through roll-to-roll casting and polymer-ceramic hybrids. In the future, development will be done on multi-ion electrolytes, digital manufacturing, and "design-manufacture-recycle" integration. Materials, engineering, and scalability will have to proceed synergistically to enable commercialization based on SSEs.

Acknowledgement

Zekai Zhang and Qitian Chen contributed equally to this work and should be considered co-first authors.

References

[1] HE B, ZHENG H, TANG K, et al. A Comprehensive Review of Lithium-Ion Battery (LiB) Recycling Technologies and Industrial Market Trend Insights [J]. Recycling, 2024, 9(1): 9.
[2] HE R, MCDONOUGH L, SEITZ L, et al. In Situ Characterization of the Oxidation Behavior of Carbonate-Based Electrolytes for Lithium-Ion Batteries by Scanning Electrochemical Microscopy [J]. ACS Electrochemistry, 2025, 1(4): 494-503.
[3] PENG Y, CHEN J, YIN Y, et al. Tailored cathode electrolyte interphase via ethylene carbonate-free electrolytes enabling stable and wide-temperature operation of high-voltage LiCoO2 [J]. Acta Physico-Chimica Sinica, 2025, 41(8): 100087.
[4] XIAO Z, WU S, REN X, et al. Superior High-Rate Ni-Rich Lithium Batteries Based on Fast Ion-Desolvation and Stable Solid-Electrolyte Interphase [J]. Advanced Science, 2025, 12(12): 2413419.
[5] LI Y, YAN Y, SHEN K, et al. High Energy Density Solid-State Lithium–Sulfur Batteries: Challenges and Advances in Cathode Materials [J]. ACS nano, 2025.
[6] WANG Z-Y, ZHAO C-Z, SUN S, et al. Achieving high-energy and high-safety lithium metal batteries with high-voltage-stable solid electrolytes [J]. Matter, 2023, 6(4): 1096-124.
[7] WU H, HU J, YU S, et al. Heterostructure conductive interface and melt-penetration-bonding process to afford all-solid-state Li–FeF 3 garnet batteries with high cathode loading [J]. Energy & Environmental Science, 2025, 18(2): 923-36.
[8] ZHANG C, YU J, CUI Y, et al. An electron-blocking interface for garnet-based quasi-solid-state lithium-metal batteries to improve lifespan [J]. Nature Communications, 2024, 15(1): 5325.
[9] NIE X, HU J, LEI M, et al. Humid-Air Stable and High-conductivity Fluoride Solid Electrolytes Induced by Liquid Metal Activation and Ga2O3 in situ Catalysis [J]. Advanced Energy Materials, 2025: 2402997.
[10] HUANG Z, WANG Z, CHEN X, et al. Interface Engineering and Optimization Strategies for High-Energy-Density Batteries Based on Polymer Composite Electrolytes [J]. Advanced Materials, 2025: e04186.
[11] YANG Q, XU J, WANG Y, et al. New fast ion conductors discovered through the structural characteristic involving isolated anions [J]. NPJ Computational Materials, 2025, 11(1): 1-10.

DOI: 10.54254/2755-2721/2026.MH30748

[12] GUO H, LI J, BURTON M, et al. High-entropy sulfide argyrodite electrolytes for all-solid-state lithium-sulfur batteries [J]. Cell Reports Physical Science, 2024, 5(10).
[13] SPENCER M A, YUN T G, FLYNN M, et al. Crystallographic Dimensionality Determines the Electrochemical Reaction Mechanism in Alkali Transition-Metal Chlorides [J]. Journal of the American Chemical Society, 2024, 146(46): 32059-71.
[14] YEANDEL S R, CHAPMAN B J, SLATER P R, et al. Structure and lithium-ion dynamics in fluoride-doped cubic Li7La3Zr2O12 (LLZO) garnet for Li solid-state battery applications [J]. The Journal of Physical Chemistry C, 2018, 122(49): 27811-9.
[15] WANG Y, THOMAS C, GARMAN K, et al. The key role of grain boundary dynamics in revolutionizing the potential of solid electrolytes [J]. Advanced Functional Materials, 2024, 34(45): 2404434.
[16] BECHER M, BECKER S, HECHT L, et al. From local to diffusive dynamics in polymer electrolytes: NMR studies on coupling of polymer and ion dynamics across length and time scales [J]. Macromolecules, 2019, 52(23): 9128-39.
[17] ZHOU Q, CHEN M, LU J, et al. Wide-temperature solid polymer electrolytes: Li+ coordination structure, ionic transport and interphases [J]. Materials Horizons, 2025, 12(10): 3201-33.
[18] JONES A L, DE KEERSMAECKER M, SAVAGIAN L R, et al. Branched oligo (ether) side chains: a path to enhanced processability and elevated conductivity for polymeric semiconductors [J]. Advanced Functional Materials, 2021, 31(35): 2102688.
[19] SHEKIBI Y, GRAY-WEALE A, MACFARLANE D R, et al. Nanoparticle enhanced conductivity in organic ionic plastic crystals: space charge versus strain induced defect mechanism [J]. The Journal of Physical Chemistry C, 2007, 111(30): 11463-8.
[20] LIU X, HOU H, WANG Y, et al. Building continuous Li-ion transport channels from cathode to anode in solid-state lithium-metal batteries [J]. Inorganic Chemistry Frontiers, 2024, 11(21): 7451-63.
[21] GAO X, LI Y, WANG W, et al. Enabling high ionic conductivity and stability of PEO-based solid electrolytes via the synergistic effect of Ga, V dual-doped garnet LLZO and plasticizer SN double fillers [J]. Journal of Alloys and Compounds, 2025, 1021: 179686.
[22] CUI J, ZHANG L, WANG M, et al. The interface compatibility between solid-state electrolytes and lithium/silicon anodes: Challenges, recent progress and perspectives [J]. Journal of Energy Storage, 2024, 101: 113774.
[23] ZHANG Y, ZHENG G, YUAN Z, et al. Review on interfacial compatibility of solid-state lithium batteries [J]. Ionics, 2023, 29(5): 1639-66.
[24] WANG J-C, WANG P-F, YI T-F. Challenges and optimization strategies at the interface between sulfide solid electrolyte and lithium anode [J]. Energy Storage Materials, 2023, 62: 102958.
[25] YUAN Z, ZHOU Y, WEI M, et al. Transient Temperature Distribution of Underground Carbon Dioxide Salt Cavern Storage With State Space Model [J]. Frontiers in Energy Research, 2020, Volume 8 - 2020.
[26] LEE S-Y, RAWAL J, LEE J, et al. Solid-State Electrolytes and Their Interfacial Properties: Implications for Solid-State Lithium Batteries [J]. Electrochemical Energy Reviews, 2025, 8(1): 9.
[27] WANG D, YIN X, WU J, et al. All-Solid-State Lithium Cathode/Electrolyte Interfacial Resistance: From Space-Charge Layer Model to Characterization and Simulation [J]. Acta Physico-Chimica Sinica, 2024, 40(7): 2307029.
[28] KANG X, LIN H, XU G, et al. Space charge layers and interface potentials in $\mathrm{Li}/\ensuremath{\gamma}\text{\ensuremath{-}}{\mathrm{Li}}_{3}{\mathrm{PO}}_{4}/{\mathrm{Li}}_{x}{\mathrm{CoO}}_{2}$ solid-state batteries: Insights from a first-principles-informed thermodynamic study [J]. Physical Review Materials, 2024, 8(10): 105402.
[29] LIANG Y, LIU H, WANG G, et al. Challenges, interface engineering, and processing strategies toward practical sulfide-based all-solid-state lithium batteries [J]. InfoMat, 2022, 4(5): e12292.
[30] HE W, ZHOU L, TUFAIL M K, et al. Space Charge Layer Effect in Sulfide Solid Electrolytes in All-Solid-State Batteries: In-situ Characterization and Resolution [J]. Transactions of Tianjin University, 2021, 27(6): 423-33.
[31] LI J, LUO J, LI X, et al. Li metal anode interface in sulfide-based all-solid-state Li batteries [J]. EcoMat, 2023, 5(8): e12383.
[32] KIMURA Y, FUJISAKI T, SHIMIZU T, et al. Coating layer design principles considering lithium chemical potential distribution within solid electrolytes of solid-state batteries [J]. Communications Materials, 2024, 5(1): 125.
[33] GUO R, ZHANG K, ZHAO W, et al. Interfacial Challenges and Strategies toward Practical Sulfide-Based Solid-State Lithium Batteries [J]. Energy Material Advances, 2023, 4: 0022.
[34] JI W, LUO B, WANG Q, et al. Interface engineering enabling thin lithium metal electrodes down to 0.78 μm for garnet-type solid-state batteries [J]. Nature Communications, 2024, 15(1): 9920.

DOI: 10.54254/2755-2721/2026.MH30748

[35] MINKIEWICZ J, JONES G M, GHANIZADEH S, et al. Large-scale manufacturing of solid-state electrolytes: Challenges, progress, and prospects [J]. Open Ceramics, 2023, 16: 100497.
[36] NING Z, JOLLY D S, LI G, et al. Visualizing plating-induced cracking in lithium-anode solid-electrolyte cells [J]. Nature Materials, 2021, 20(8): 1121-9.
[37] KAZYAK E, GARCíA-MéNDEZ R. Recent progress and challenges for manufacturing and operating solid-state batteries for electric vehicles [J]. MRS Bulletin, 2024, 49(7): 717-29.
[38] CHOI S, KIM U, ROH Y, et al. Roll-to-roll fabrication and characterization of ultra-thin ceramic-coated separator for high-energy-density lithium-ion batteries [J]. Journal of Power Sources, 2024, 623: 235427.
[39] HOROWITZ Y, LIFSHITZ M, GREENBAUM A, et al. Review—Polymer/Ceramic Interface Barriers: The Fundamental Challenge for Advancing Composite Solid Electrolytes for Li-Ion Batteries [J]. Journal of The Electrochemical Society, 2020, 167(16): 160514.
[40] WU Y, ZHANG Z, ZHANG Q, et al. Industrialization challenges for sulfide-based all solid state battery [J]. eTransportation, 2024, 22: 100371.
[41] LIU Q, WANG H, JIANG C, et al. Multi-ion strategies towards emerging rechargeable batteries with high performance [J]. Energy Storage Materials, 2019, 23: 566-86.
[42] WINDISCH-KERN S, GEROLD E, NIGL T, et al. Recycling chains for lithium-ion batteries: A critical examination of current challenges, opportunities and process dependencies [J]. Waste Management, 2022, 138: 125-39.
[43] HUANG J, SHOAI NAINI S, MILLER R, et al. Development of a heat pipe–based battery thermal management system for hybrid electric vehicles [J]. Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering, 2020, 234(6): 1532-43.