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Key Challenges and Strategies for Commercialization of All-Solid-State Batteries: Materials, Interface Engineering, and Manufacturing Processes

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ABSTRACT

All-solid-state batteries (ASSBs) are promising next-generation batteries that can improve the safety and energy density limitations of conventional lithium-ion batteries (LIBs). This review article analyzes ASSB commercialization from the perspectives of solid electrolytes, interface engineering, manufacturing processes, and system integration. The results indicate that no single electrolyte satisfies all requirements for ionic conductivity, electrochemical stability, mechanical deformability, moisture tolerance, cost, and processability. Halide-based electrolytes are particularly promising for high-voltage cathode composites because they can suppress interfacial degradation and reduce the need for protective coatings. Interface analysis further shows that contact loss, space-charge-layer (SCL) formation, side reactions, dendrite growth, and microcracking are strongly coupled degradation mechanisms. For scalable manufacturing, dry processing, sheet-type fabrication, low-temperature densification, and solution-based halide synthesis are identified as key strategies. Overall, ASSB commercialization requires an integrated framework linking materials design, interface stabilization, process scalability, pressure and thermal management, and solid-state-specific battery management systems (BMSs).

1 | Introduction

As global environmental concerns intensify, the transition toward sustainable technologies such as electric vehicles (EVs), renewable energy integration, and energy storage systems (ESSs) has become imperative to achieve carbon neutrality (refer to the Nomenclature section) [1, 2]. The effective implementation of these solutions relies heavily on advanced power sources that can provide both high-energy density and enhanced safety to manage the high-power demands of EVs and the inherent intermittency of renewables within ESS frameworks [1]. In

renewable-energy-linked ESS applications, especially those coupled with photovoltaic and wind power generation, storage devices must balance fluctuating power supply and demand while maintaining high-energy density, rapid charge–discharge response, and long cycle stability. Therefore, all-solid-state batteries (ASSBs) should be evaluated not only as high-energy batteries but also as storage platforms that can improve the efficiency, reliability, and stability of renewable energy integration [1]. Consequently, with the proliferation of these critical applications, the limitations of conventional lithium-ion batteries (LIBs) are gradually becoming prominent [3–7]. Although LIBs

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have rapidly evolved since their commercialization in 1991, safety issues persist due to the flammability and leakage risk of organic liquid electrolytes, and the challenges associated with lithium-metal (Li-metal) anodes fundamentally limit the extent to which the energy density of LIBs can be improved [3, 4, 8–10]. Specifically, Li-metal is ideal for high-power and high-energy-density applications because of its high theoretical capacity; however, in a liquid electrolyte environment, lithium dendrite growth occurs, which reduces the battery's cycle life and causes short-circuits, thereby hindering practical application [3, 4, 8, 9, 11]. As a solution to these issues, ASSBs have attracted attention as next-generation energy storage technology [3–5, 7, 10].

Figure 1 schematically illustrates the evolution from conventional LIBs to high-energy-density Li-metal batteries, highlighting the role of solid electrolytes and the associated technical challenges in this process.

As shown in the schematic on the left of Figure 1, conventional LIBs utilize graphite anodes to ensure high stability; however, their low theoretical capacity limits improvements in energy density. To overcome this limitation, introducing a high-capacity Li-metal anode, as shown in the center, presents a critical drawback in a liquid electrolyte environment: dendritic Li growth penetrates the separator, leading to electrolyte decomposition and internal short-circuits.

In contrast, the ASSB system on the right demonstrates that replacing the liquid electrolyte with a solid electrolyte physically suppresses dendritic Li growth and reduces the risk of explosion. However, as indicated at the bottom of the Figure 1, realizing an ideal solid electrolyte system requires overcoming the inherent disadvantages of solid electrolytes, such as low ionic conductivity, high interfacial resistance between the electrode and electrolyte, and issues related to moisture stability.

This article describes specific technical solutions for meeting these requirements from the perspectives of materials, interfaces, and processes.

By replacing the liquid electrolyte in conventional LIBs with a solid material, ASSBs achieve nonvolatility and nonflammability [3, 4, 7, 10, 12]. Furthermore, since the solid electrolyte can be combined with a Li-metal anode, ASSBs can attain a theoretical energy density of ~500–900 Wh/kg based on a combination of a Li-metal anode and a high-voltage anode (e.g., $\text{LiNi}_x\text{Mn}_y\text{Co}_z\text{O}_2$ [NMC] or LiCoO_2 [LCO]) [3–5, 11, 13].

Studies have reported that utilizing an all-solid-state structure offers advantages such as approximately two to three times the energy density and more than twice the lifespan of conventional LIBs, as well as superior high-temperature stability [3–7]. Additionally, solid electrolytes are compatible with silicon-based anodes and high-voltage (4.5 V) cathodes, which is expected to help improve single-charge driving range and facilitate ultrafast charging for EVs [4, 8, 9, 13, 14]. The all-solid-state structure is expected to ensure stable compatibility with silicon-based high-capacity cathodes and high-voltage cathodes (4.5 V or higher), thus contributing to innovations in EV performance, such as improved single-charge driving range and ultrafast charging [4, 6].

Currently, major international companies, such as Samsung SDI, QuantumScape, and Solid Power, are accelerating technological development to facilitate the commercialization of ASSBs. The number of related patent applications and published papers is rapidly increasing, particularly in the United States of America, Japan, and South Korea [3, 15]. Nevertheless, certain technological barriers continue to impede the practical application of ASSBs [5, 7, 11, 13, 16]. The key challenges include improving the ionic conductivity of solid electrolytes and establishing an industrial-scale process for their synthesis; addressing solid–solid interfacial resistance; suppressing lithium dendrite growth; developing large-area, high-density cell-manufacturing processes; achieving room-temperature operation and stable cycling; and managing cost and raw-material availability [8, 9, 11, 13, 16]. Accordingly, these challenges are categorized into four domains—materials, interface, process, and outlook—to systematically organize the associated technological trends [15].

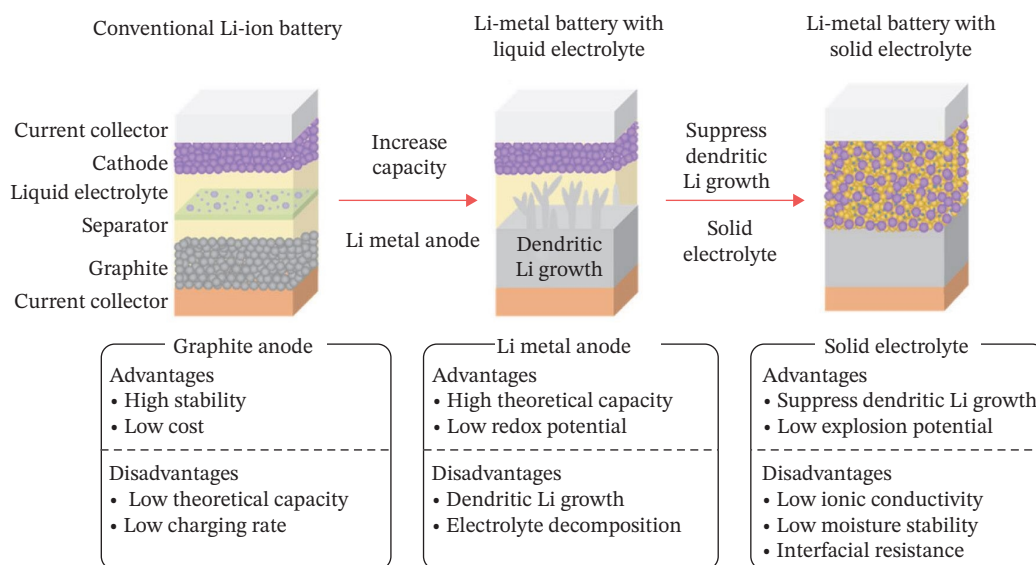


FIGURE 1 | Schematic comparison of the evolution from conventional Li-ion batteries to Li-metal batteries with solid electrolytes, highlighting the advantages and disadvantages of each system. Reprinted with permission from Park et al. [12], Copyright 2023, Wiley.

Solid electrolytes are categorized into oxide-based, sulfide-based, halide-based, and polymer-based materials. Herein, the characteristics of these materials are compared, their respective advantages and disadvantages are outlined, and improvement strategies are suggested based on recent research findings [17–21].

Interface stabilization technologies include reducing the interfacial resistance between solid electrolytes and electrode materials, applying coatings to suppress chemical reactions, adding buffer layers, and performing in situ analysis [9, 14, 18–20]. Regarding manufacturing processes, this review article summarizes strategies for high-integration and large-area development recently adopted by the industry, such as thin-film or stack-type processes and slurry-based electrolyte sheet processes [11, 13, 16, 19, 20].

Overall, this review article comprehensively examines the key challenges related to ASSB technology, highlighting directions for future researchers and development. Unlike previous review articles that mainly focus on individual electrolyte chemistries or isolated interfacial reactions, this review article provides a commercialization-oriented framework that connects solid electrolyte selection, cathode/anode interface engineering, scalable manufacturing processes, data-driven materials design, and system-level integration. By analyzing the fundamental bottlenecks in ASSB commercialization from a materials-engineering perspective, this review article emphasizes the need for interdisciplinary research spanning materials design, interface engineering, manufacturing technology, and intelligent battery management [5, 7, 11].

2 | Solid Electrolytes: Material Challenges and Engineering Strategies

ASSBs have many similarities with conventional LIBs in terms of their basic structure and operating principles [22–24]. While both share a common structure, with the electrolyte acting as a medium for ion transport between the cathode and the anode, the key difference lies in the electrolyte's phase, i.e., solid or liquid [3, 25, 26]. Although LIBs utilize liquid electrolytes, which facilitate rapid ion transport during charging and discharging, their safety is limited due to flammability and leakage risks

[27–30]. By contrast, the use of solid electrolytes in ASSBs minimizes leakage risks and maintains structural stability even under external impacts [25, 31, 32].

Solid electrolytes are composed of crystalline or polymeric materials and are attracting attention as suitable materials for next-generation ESSs as they simultaneously ensure ionic conductivity and mechanical strength [3, 33, 34]. Lithium ions move along ionic conduction paths within solids, which drives the charging and discharging processes [7, 35, 36]. In ASSBs, the solid electrolyte is a critical component determining the battery's performance and safety [26, 27, 37]. Solid electrolytes must provide a conductive path for lithium ions while blocking electronic conduction. Therefore, they require a specific combination of properties, including high ionic conductivity ($>10^{-3}$ S/cm), chemical stability, interfacial stability, and mechanical strength [38, 39].

Solid electrolytes are classified as oxide-based, sulfide-based, polymer-based, or halide-based, depending on their properties and composition [10, 17, 40, 41]. Figure 2 illustrates the classification of various solid electrolyte materials applicable to ASSB systems.

As shown in Figure 2, solid electrolytes are broadly categorized into polymers, which offer flexible processability, and inorganic electrolytes, which feature high ionic conductivity [13, 20, 41]. Inorganic electrolytes are subdivided into oxides and sulfides, based on their crystal structure and constituent elements [17, 18, 43].

Particularly noteworthy is the unconventional material group on the right side of the Figure 2. Halide-based electrolytes, once considered unsuitable for ASSBs, have recently been reevaluated as materials that combine the high-voltage stability of oxides with the mechanical advantages of sulfides. Hence, they are rapidly emerging as one of the four key materials for next-generation ASSBs [10, 19, 44–46]. The following subsections discuss the characteristics of each material group in depth and outline suitable performance improvement strategies accordingly.

Each material group has advantages and disadvantages in terms of ionic conductivity, electrochemical stability, processability, and stability in air, and its suitability varies depending on the intended application [26, 27].

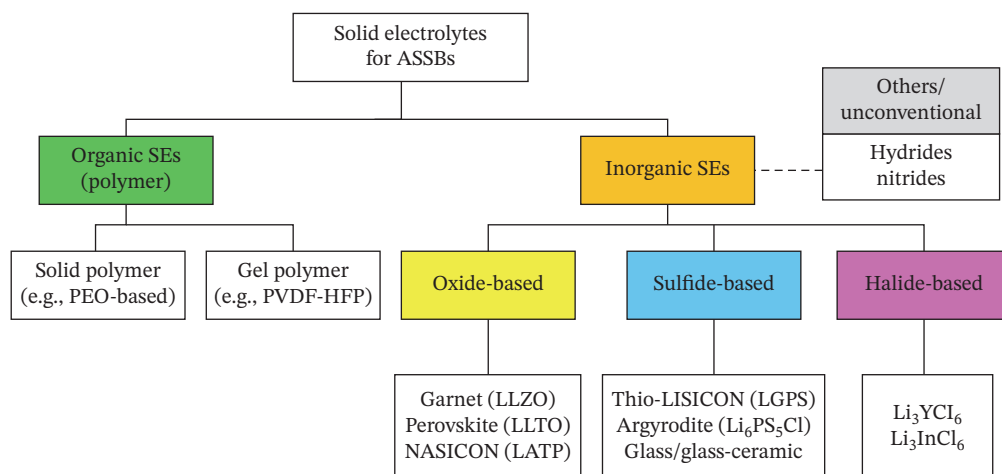


FIGURE 2 | Classification of solid electrolyte materials for ASSBs. Reprinted with permission from Joshi et al. [42], Copyright 2025, Elsevier.

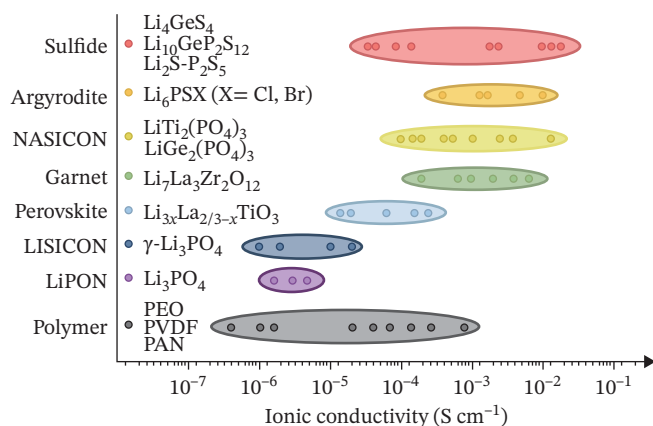


FIGURE 3 | Ionic conductivities of various types of solid electrolytes. Reprinted with permission from Park et al. [12], Copyright 2023, Wiley.

Figure 3 compares the ionic conductivity ranges of major solid electrolyte materials. As seen in the graph, sulfide-based electrolytes exhibit the highest conductivity, followed by oxide-based electrolytes (e.g., garnet-based electrolytes) and then polymer-based electrolytes [3, 5, 47–49].

The following subsections detail the properties of each electrolyte material and the associated technical issues.

2.1 | Oxide-Based Solid Electrolytes

2.1.1 | Characteristics and Key Challenges

A representative oxide-based solid electrolyte is $\text{Li}_7\text{La}_3\text{Zr}_2\text{O}_{12}$ (LLZO) [17, 50–52], which possesses a garnet crystal structure, boasts a high Li^+ conductivity of 10^{-3} S/cm, and exhibits a relatively wide electrochemical stability window (ESW) at the interface with high-voltage cathodes and Li-metal anodes [17, 53–55].

A significant advantage of LLZO is its excellent electrochemical stability, which allows it to form stable interfaces with both Li-metal anodes and 5-V-class cathodes [17, 56, 57]. Specifically, because oxides are chemically stable and moisture-resistant, they are relatively safe to handle even in air [9, 58–60]. However, the possibility of electron leakage at grain boundaries within the polycrystalline structure—which may lead to the formation of lithium dendrites and penetration of the solid electrolyte, resulting in cell short-circuits—must be addressed [8, 11, 17, 61–64].

As shown in Figure 4, garnet-type oxide electrolytes exhibit excellent thermal and chemical stability and a wide ESW; however, their processability requires improvement, and their manufacturing costs must be lowered [6, 17, 65, 66].

2.1.2 | Engineering Strategies: Interface Stabilization and Structural Control

Oxide-based solid electrolytes, such as the aforementioned garnet-type LLZO, have been extensively studied as core electrolyte materials for ASSBs due to their excellent chemical stability and relatively high ionic conductivity [17]. Thus far, LLZO electrolytes have been implemented in milliwatt-hour-class small cells in combination with Li-metal anodes and 5 V cathodes. However, their commercialization remains challenging, primarily due to

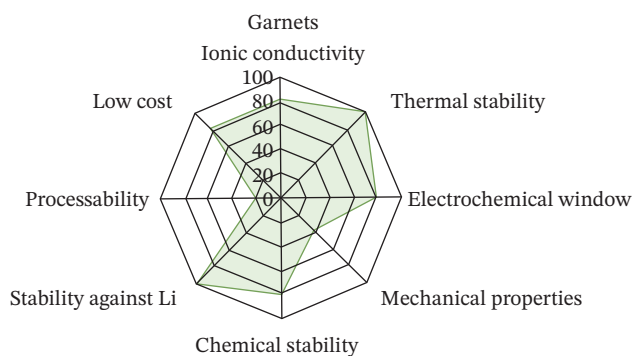


FIGURE 4 | Performance radar chart for garnet-type solid electrolytes (e.g., LLZO). Reprinted with permission from Moradi et al. [7], Copyright 2023, Elsevier.

grain-boundary resistance and lithium infiltration within the sintered polycrystalline body. Electrical inhomogeneity at grain boundaries can cause localized current concentrations, leading to Li-metal growth along microscopic defects and dendritic short-circuiting through the electrolyte [11, 17]. Various materials engineering approaches have recently been proposed to address this issue. The main strategies include (i) eliminating grain boundaries by monocrystallizing or amorphizing the electrolyte into a glassy state [17, 67], (ii) doping fine grain boundaries with additives to control electrical properties and enhance mechanical strength [11, 68–70], and (iii) creating uniform and dense electrolyte films via thin-film coating processes based on laser annealing or low-temperature sintering [17, 71–73]. For example, researchers have partially amorphized LLZO through a slab-quench process with controlled cooling rates to create a structure in which lithium cannot easily penetrate grain boundaries, while a dense LLZO thin film (several micrometers thick) has also been applied as a coating layer via pulsed laser deposition [17, 74]. The goal of these efforts was to achieve a balance between ionic conductivity and mechanical stability for oxide electrolytes. To date, the critical current density has been successfully enhanced (~ 0.5 mA/cm² or more) while maintaining the ionic conductivity at $\sim 1 \times 10^{-3}$ S/cm [17, 75, 76].

From a commercialization perspective, although oxide-based solid electrolytes offer excellent chemical stability, their high sintering temperature, brittleness-related interfacial contact loss, and high interfacial resistance limit their applicability in the electrode stack structures required for high-energy-density batteries [6, 17, 65].

2.2 | Sulfide-Based Solid Electrolytes

2.2.1 | Characteristics and Key Challenges

Sulfide-based solid electrolytes are typically represented by $\text{Li}_{10}\text{GeP}_2\text{S}_{12}$ (LGPS) and $\text{Li}_6\text{PS}_5\text{Cl}$ (argyrodite structure) [48, 77]. These materials exhibit excellent ionic conductivity, typically in the range of several millisiemens per centimeter at room temperature, which is the highest among solid electrolyte materials [48]. Furthermore, they offer distinct structural advantages, such as excellent particle-to-particle contact that facilitates interface formation with active materials. Their high plastic deformability also ensures minimal interfacial resistance during the fabrication of electrode composites [5]. However, sulfide-based materials are

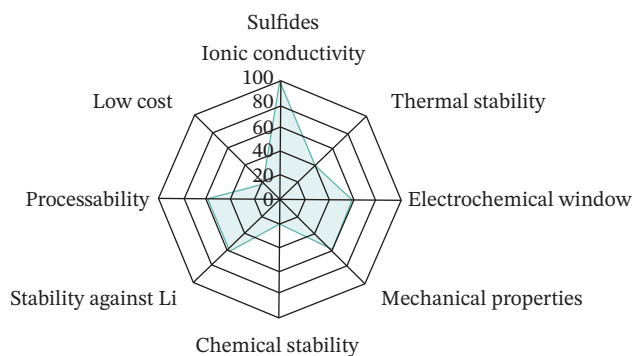


FIGURE 5 | Performance radar chart of sulfide-based solid electrolytes (e.g., LGPS). Reprinted with permission from Moradi et al. [7], Copyright 2023, Elsevier.

highly sensitive to moisture in the air, generating toxic hydrogen sulfide (H_2S) gas through hydrolysis upon exposure; hence, their manufacturing and handling processes are difficult to control [5]. Additionally, when in contact with a high-voltage cathode (≥ 4 V), S^{2-} ions undergo oxidation and decompose at the interface, forming nonconductive inert byproducts (such as space charge layers (SCLs), which limit interfacial stability [78, 79]. Consequently, although the initial performance of sulfide-based electrolytes is excellent, the increase in their resistance and the reduction in their capacity due to the growth of interfacial reaction layers during long-term cycling constitute major problems [78].

Figure 5 illustrates the trade-offs associated with sulfide-based electrolytes. As shown in the chart, these electrolytes exhibit superior ionic conductivity compared with other materials [5]. However, they exhibit very poor chemical stability in the presence of moisture and a limited ESW at high voltages; therefore, surface coating technologies are needed to compensate for these limitations [78].

2.2.2 | Engineering Strategies: Interface Stabilization and Structural Control

To address the moisture sensitivity and high-voltage interface instability of sulfide-based electrolytes, recent research has focused on strategies such as (i) protective surface coating, (ii) ion substitution (doping), and (iii) composite electrolyte design.

Protective surface coatings encapsulate the surface of sulfide particles with a thin oxide or polymer film to prevent direct moisture contact when exposed to air [78]. For example, coating the surface of argyrodite-based $\text{Li}_6\text{PS}_5\text{Cl}$ particles with a stable oxide layer, such as Li_2SiO_3 or Li_3BO_3 , has been reported to improve stability in air while simultaneously suppressing the oxidation and decomposition of sulfides upon contact with the anode.

To enhance stability, the electron density within the crystal structure can be controlled through ion substitution (doping) [79]. Partial substitution with halide anions (e.g., Cl^- doping) can block the electron conduction path of sulfides, enhancing their oxidation stability [79]. For instance, a $\text{Li}_{10}\text{GeP}_2\text{S}_{12-x}\text{Cl}_x$ compound, in which some of the sulfur (S) anions in the LGPS structure are replaced with halide anions, such as chlorine (Cl), was

found to achieve significantly higher contact stability with high-voltage anodes, such as LCO, while maintaining high ionic conductivity.

Composite electrolyte design is a strategy that combines sulfides with a stable oxide or polymer matrix to achieve complementary properties [77]. These inorganic–inorganic or inorganic–organic composite electrolytes feature a balanced design that leverages the high conductivity of sulfides while simultaneously ensuring moisture stability and electrochemical stability [48, 77].

From a commercialization perspective, sulfide-based solid electrolytes offer the advantages of high ionic conductivity and processability. However, their sensitivity to moisture, interfacial chemical instability, and reactivity with anodes under high stack pressures considerably limit process reliability in large-scale production environments.

2.3 | Polymer-Based Solid Electrolytes

2.3.1 | Characteristics and Key Challenges

Polymer electrolytes are formed by mixing lithium salts into a polymer matrix, such as polyethylene oxide (PEO) or polyvinylidene fluoride (PVDF). These materials offer excellent flexibility and can be manufactured as thin-film coatings; hence, they are ideal for large-area battery production, such as through roll-to-roll processes [20]. Furthermore, they can be manufactured at low temperatures, specifically below room temperature, which ensures high thermal compatibility with electrode materials.

However, due to limited ion mobility in the solid state, the room-temperature ionic conductivity of polymer electrolytes is typically low, on the order of 10^{-5} – 10^{-4} S/cm [20]. Hence, their effectiveness is limited because high-temperature operation ($>60^\circ\text{C}$) is required to ensure optimal battery performance [13]. Furthermore, their lower mechanical strength compared with inorganic electrolytes hinders the physical suppression of lithium dendrite growth during charging and discharging, thereby posing a risk of short-circuits [20, 80].

The performance radar chart in Figure 6 comprehensively illustrates the characteristics of polymer-based solid electrolytes. As observable in the chart, these electrolytes are significantly more processable and cost-effective than other materials, which

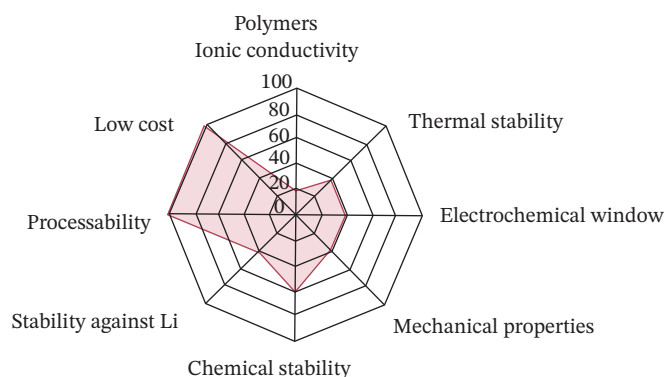


FIGURE 6 | Performance radar chart of polymer-based solid electrolytes (e.g., PEO). Reprinted with permission from Moradi et al. [7], Copyright 2023, Elsevier.

demonstrates their suitability for large-scale production, such as roll-to-roll processes [20]. Conversely, their ionic conductivity and mechanical properties are relatively inferior, which highlights the inherent limitations of polymer materials. This stark trade-off between manufacturability and electrochemical/mechanical performance necessitates advanced engineering strategies, such as complexation and structural control [81].

2.3.2 | Engineering Strategies: Interface Stabilization and Structural Control

To address the inadequate room-temperature ionic conductivity and mechanical strength of polymer electrolytes, composite design and process optimization strategies have been actively pursued.

2.3.2.1 | Composite Preparation Using Inorganic Nanofillers. This method involves dispersing ceramic particles, such as Sodium super ionic conductor (NASICON) glass ceramics or LLZO nanopowders, in a polymer matrix [13]. Inorganic fillers promote lithium-ion transport by inhibiting polymer-chain crystallization and provide additional pathways for ion diffusion along the inorganic surface, thereby enhancing conductivity [82]. They also enhance the polymer's mechanical strength, preventing interfacial separation [82]. For example, the addition of tens of weight percent of LLZO particles measuring 10–20 nm has been reported to significantly improve the conductivity of PEO at room temperature [82].

2.3.2.2 | In Situ Polymerization. This technology involves injecting a liquid monomer after coating the electrode composite before inducing a polymerization reaction with heat or light during the battery assembly process to form a polymer electrolyte. This technique dramatically improves adhesion by filling the microscopic voids between the electrode and the electrolyte [28]. A recent study showed that when using an oligoethylene glycol-based monomer compatible with sulfide electrolytes, the polymerization reaction is induced within the cathode composite, which produces a sulfide–polymer hybrid network and significantly reduces interfacial resistance [28].

Research on polymer electrolytes has thus focused on overcoming the trade-off between conductivity and mechanical properties. Recently, materials approaching the critical conductivity (10^{-4} S/cm) for room-temperature operation have been reported [20, 28]. Regarding commercialization, while polymer-based solid electrolytes offer excellent flexibility and process suitability, their utility as a sole electrolyte is structurally limited by their low ionic conductivity at room temperature and the mechanical control limitations of Li-metal anodes [26].

2.4 | Halide-Based Solid Electrolytes

2.4.1 | Characteristics and Key Challenges

Halide-based electrolytes have recently gained research attention, with chloride-based lithium electrolytes, such as Li_3InCl_6 and Li_3YCl_6 , being representative examples. These electrolytes simultaneously achieve wide voltage stability (>4.5 V) and high ionic conductivity ($\sim 10^{-3}$ S/cm). Furthermore, they possess

superior oxidation stability compared with sulfide electrolytes, which significantly suppresses interfacial reactions, even in direct contact with high-voltage cathodes (NMC series, ≥ 4 V) [46, 83]. Moreover, they exhibit excellent mechanical deformability, which facilitates the formation of physical contact surfaces with electrode particles [46].

However, like sulfide electrolytes, halide electrolytes are extremely sensitive to moisture and thus require a rigorously maintained dry-room environment during synthesis and battery assembly, which represents a key challenge [46]. Furthermore, as initial research primarily relied on expensive rare-earth metals, such as yttrium (Y) and indium (In), cost reduction is essential for enabling the mass production of halide electrolytes [47]. Nevertheless, due to their strong potential for high-voltage performance and excellent chemical compatibility with cathode materials, they are being evaluated as a viable option for next-generation cathode composites [83].

2.4.2 | Engineering Strategies: Material Optimization and Cost Reduction

Research efforts to commercialize halide-based electrolytes have focused on (i) optimizing the interface with high-voltage cathodes and (ii) reducing material costs and ensuring processability.

Strategies are needed to leverage the high-voltage cathode compatibility of halide-based electrolytes. Because materials such as Li_3InCl_6 and Li_3YCl_6 are electrochemically stable even in the 4–5 V range, they can be combined with high-nickel (high-Ni) cathodes, such as $\text{LiNi}_{0.8}\text{Co}_{0.1}\text{Mn}_{0.1}\text{O}_2$ (NCM811), without a separate protective coating, which minimizes the increase in interfacial resistance [83]. Based on this principle, a high-voltage all-solid-state cell, recently developed using a “dual-electrolyte” design—featuring a halide electrolyte as the cathode composite and sulfide or Li-metal only on the cathode side—achieved a capacity retention rate of 80% over 100 cycles [46, 83].

Cost reduction and process improvement strategies are also being developed. To reduce the high raw-material costs that hinder commercialization, novel compositions (Li_2ZrCl_6) using inexpensive zirconium (Zr) or iron (Fe) as the core metal instead of expensive rare-earth elements (Y, In) are being actively pursued [47]. Furthermore, researchers have attempted to coat the surface of the electrolyte particles with oxides to prevent performance degradation upon exposure to air, in addition to exploring the feasibility of mass production via solution-based (wet) synthesis instead of solid-state synthesis for cost reduction [46, 47]. Halide SSEs uniquely reconcile the stability-conductivity-processability trade-offs that challenge other electrolyte systems, particularly through their ability to be processed at room temperatures and pressures, which simplifies the transition from laboratory-scale research to pilot-scale production [84]. Furthermore, while ionic conductivity typically ranges from 10^{-4} to 10^{-2} S/cm, recent manufacturing strategies using solution-based synthesis have demonstrated a potential 65% reduction in production energy consumption compared to energy-intensive oxide SSEs [84].

From a commercialization viewpoint, halide-based solid electrolytes are emerging as promising candidates based on their

excellent chemical stability with high-voltage anodes; however, they still require long-term verification because of their relatively low ductility, insufficient manufacturing process maturity, and inadequate interfacial mechanical stability [45].

2.5 | Integration of Li-Metal Anode and Technical Challenges

The technological advantage of ASSBs is evident in their ability to use Li-metal as the anode. While traditional graphite anodes have a theoretical capacity of ~ 372 mAh/g, Li-metal offers a 10-fold higher capacity of ~ 3860 mAh/g, thereby significantly increasing the energy density of the cell [85]. However, the high reactivity of Li-metal induces dendrite formation upon direct contact with the electrolyte. Specifically, dendrites growing through defects or microcracks in the solid electrolyte can cause short-circuits within the cell [86]. Therefore, ASSB designs must incorporate strategies such as structural modification to suppress dendrite formation, the introduction of electronically insulating interfacial layers, and the minimization of grain-boundary defects.

2.5.1 | Failure Mechanism: Electronic Conductivity and Voids

Recent studies have shed new light on the causes of lithium dendrite formation, exploring electrochemical and physical properties rather than simple mechanical failures. Specifically, the subtle electronic conductivity within the solid electrolyte has been found to induce lithium reduction within the electrolyte, thereby promoting dendrite nucleation [85]. Furthermore, voids formed at the interface when lithium escapes from the anode during discharge reduce the interfacial contact area, causing localized current densities to exceed a critical value (current hotspot), which is a key factor in accelerating dendrite growth during the next charge [86]. Therefore, appropriate stack pressure control and interface design techniques are essential for maintaining mechanical contact at the interface [87].

2.5.2 | Advanced Anode Strategies: Silver–Carbon Layer and Anode-Free Design

Technologies that rely on “anode-free” processing or “composite anodes” instead of directly utilizing Li-metal are attracting attention as the key to the commercialization of ASSBs. The most notable accomplishment in this regard was achieved by the Samsung Advanced Institute of Technology, where researchers coated the current collector with a silver–carbon (Ag–C) nanocomposite layer to induce uniform deposition/desorption of lithium, thereby fundamentally suppressing dendrite growth. This technology was successfully employed to operate a large-area pouch cell with a high-energy density (>900 Wh/L) and a cycle life of over 1000 cycles [88]. Furthermore, an anode-free process technology that completely excludes the initial Li-metal and allows only the lithium transferred from the anode to be plated on the anode current collector during charging is being actively researched as a strategy for reducing process costs and maximizing energy density [89].

3 | Advanced Electrode Design and Interface Engineering

3.1 | Cathode Materials and Interface Control

3.1.1 | Challenges: SCL and Side Reactions

Composite cathodes for ASSBs have a 3D structure consisting of active material, solid electrolyte, and conductive material [5, 90]. The basic all-solid-state cell structure is based on an [anode | solid electrolyte | cathode] configuration; the thickness and density of the solid electrolyte layer and the contact characteristics of the electrode–electrolyte interface significantly affect the internal resistance and capacity characteristics of the battery [5, 90, 91].

Generally, ion channels are secured by dispersing solid electrolyte particles within the composite electrode layer to shorten the ion conduction paths and reduce internal resistance [90, 92]. Specifically, composite cathodes are designed with an optimized active material/solid electrolyte/conductive material mass ratio of $\sim 70:25:5$ to ensure a balance between ion and electron conduction [5, 90].

Figure 7 illustrates the percolation network of ions and electrons formed within the composite anode of an ASSB, as well as the transport barriers at the solid interface. As conductive batteries rely on “point contact” between solid particles, imperfect physical contact between particles can disrupt ion conduction [5, 90, 91].

Even if physical contact is achieved, the chemical potential difference between an oxide anode and a sulfide electrolyte causes lithium ions to redistribute, thereby producing an SCL [79, 94]. This layer acts as a high-resistance barrier with a low lithium concentration at the interface, constituting a major cause of battery performance degradation. Therefore, an interface engineering approach is essential for controlling this layer [79, 94, 95].

Since both the electrode and electrolyte are solid, achieving complete contact at the interface is difficult. Hence, process optimization techniques, such as applying pressures exceeding several megapascals or inserting an interface modification layer during battery manufacturing, are essential [91, 96, 97].

Specifically, when an oxide cathode and a sulfide electrolyte come into contact, the chemical potential difference between the two materials can cause lithium ions to migrate, which produces an SCL. Furthermore, the sulfide can oxidize and decompose, forming a nonconductive film. This can lead to a rapid increase in interfacial resistance [78, 79, 94], impeding electron flow and thus reducing battery capacity [78, 91, 94].

3.1.2 | Chemomechanical Issues: Volume Expansion and Contact Loss

In addition to chemical instability, chemomechanical failure is a key factor in performance degradation [96, 97]. With repeated charge–discharge cycles, the active material particles in the positive electrode expand and contract due to lithium insertion and deintercalation, which causes contact loss between the electrode and the electrolyte [96–98]. This mechanical discontinuity reduces the effective reaction area and causes microcracks within the particles, thereby shortening the battery life [96, 98, 99]. Therefore, a flexible interface design that considers the mechanical properties of the battery materials is essential [91, 96, 98].

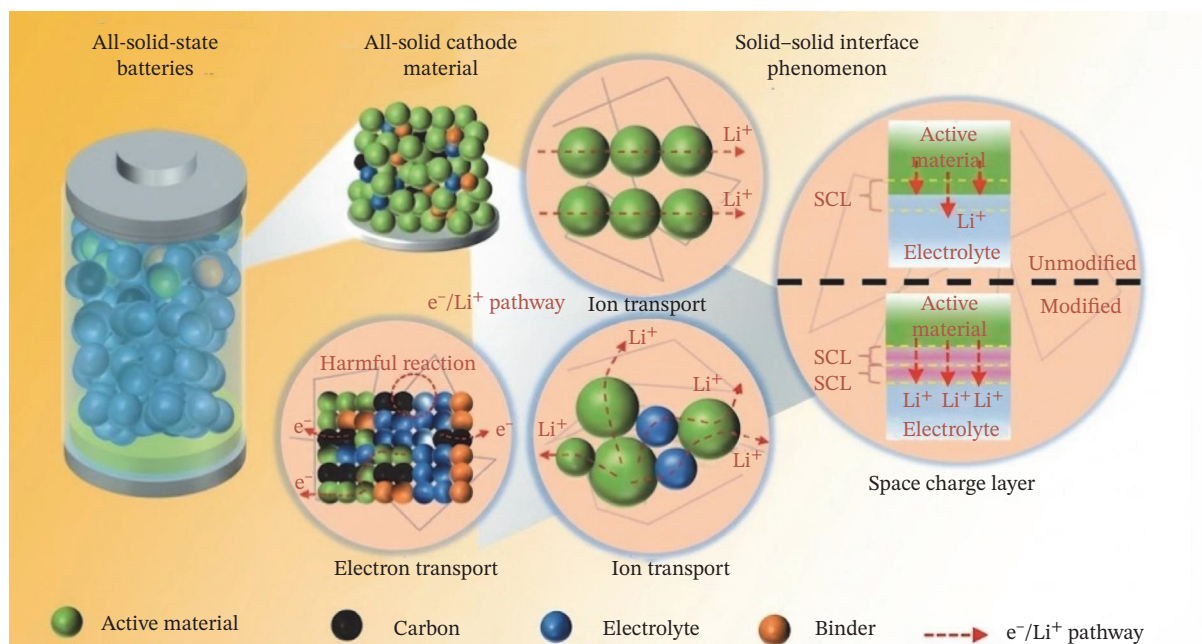


FIGURE 7 | Schematic illustrating ion and electron transport percolation networks within a composite cathode, along with solid-solid interface phenomena, including the SCL. Reprinted with permission from Dong et al. [93], Copyright 2023, Wiley.

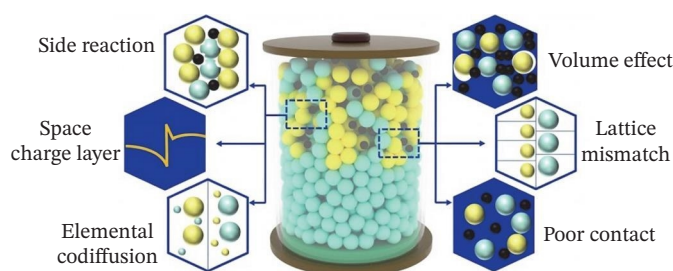


FIGURE 8 | Schematic illustrating critical interface degradation mechanisms in the cathode composite of ASSBs. Reprinted with permission from Gao et al. [14], Copyright 2024, Elsevier.

Figure 8 comprehensively illustrates how the electrochemical and mechanical challenges manifest within a composite anode. Due to thermodynamic instability, side-reaction products and an SCL are formed at the active material–electrolyte interface, which acts as a resistive barrier impeding ion transport [78, 79, 94]. Simultaneously, the volume change of the active material accompanying the charge–discharge process induces debonding—i.e., breakage of the physical bonds between particles—and microcracks within the particles, permanently damaging the conductive network [96, 98, 99]. In summary, the Figure 8 demonstrates that improving individual battery components separately is insufficient for achieving optimal performance; instead, a comprehensive interface stabilization strategy that simultaneously controls chemical and mechanical defects is necessary [91, 96, 97].

3.1.3 | Engineering Strategies: Single-Crystal Cathodes, Surface Coating, and Composite Design

One of the strategies to overcome chemical and mechanical instabilities is controlling the particle structure of the cathode

active material [98, 99]. Conventional polycrystalline cathodes are prone to microcracks, which occur at grain boundaries due to stress accumulation within the particles during charge and discharge [98, 99]. These microcracks expose new interfaces, accelerating side reactions with the electrolyte. Therefore, recent research has focused on suppressing gas generation and extending the battery lifespan by employing single-crystal cathodes with no internal particle defects and superior mechanical integrity [98–100].

Furthermore, the cathode surface should be concurrently nano-coated with ion-conducting oxides, such as LiNbO_3 and Li_2ZrO_3 [78, 95, 101]. Such coating (buffer) layers prevent direct chemical reactions with the electrolyte and suppress the formation of SCLs, drastically reducing the interfacial resistance.

Furthermore, composite cathode design technologies are being developed to simultaneously enhance energy density and output characteristics by adjusting the ratio of the particle sizes of the active material and electrolyte or introducing a graded dispersion structure to optimize the ion/electron conduction network within the electrode [5, 90, 91]. Moreover, “dynamic self-healing interface” technology, which repairs microcracks that occur during cycling, is attracting attention [96, 98]. This innovative strategy extends battery life by incorporating small amounts of polymers or low-melting-point glass materials that fluidize according to volume changes during charge and discharge, thereby inducing reconnection whenever physical contact is lost [96, 102].

3.1.4 | Advanced Strategy: Halide-Based Composite Cathode

Actively introducing halide-based electrolytes into composite cathodes has recently emerged as an alternative to using sulfide-based electrolytes [46, 83]. Halide electrolytes (e.g., Li_3InCl_6

and Li_3YCl_6) undergo virtually no oxidative decomposition, even when in direct contact with oxide anodes, and maintain excellent stability, even at voltages exceeding 4.5 V [45, 46, 83].

Halide materials exhibit lower electronic conductivity than sulfide materials, which can fundamentally prevent electron leakage within the anode. Furthermore, their superior inherent deformability allows for maximizing the physical contact area with electrode particles [46, 47]. Specifically, halide SSEs are identified as a key enabler for the commercialization of high-voltage ASSBs because they can eliminate the need for costly cathode protective coatings, thereby streamlining the overall manufacturing process [84]. Recent advancements also highlight the “dynamic stability window” of halide electrolytes, where reversible redox activity allows them to function as active components at the interface, further improving overall battery performance and durability [84]. This suggests that halide materials are being regarded as more than mere substitutes; they are becoming essential elements in the design of high-performance ASSBs [46, 103].

3.2 | Li-Metal Anode Stabilization

3.2.1 | Theory and Key Issues: Dendrite Growth

Li-metal has a theoretical capacity (3860 mAh/g) ~10 times that of graphite, as well as the lowest operating voltage (−3.04 V); hence, it represents an ideal anode material for maximizing energy density [29, 30, 32, 55]. However, Li-metal has a fatal flaw: when lithium is unevenly deposited during charging, dendrites—sharp dendritic crystals—grow, penetrating the solid electrolyte and causing short-circuits [27, 62, 63, 65]. Specifically, grain boundaries and voids within the solid electrolyte serve as primary pathways for dendrite growth [63, 65, 85, 86]. Additionally, during the repetitive plating/stripping process, some of the lithium is isolated from the conductive network and cannot react electrochemically, forming “dead lithium”; this depletes the available lithium source and is the main cause of rapid declines in the capacity and Coulombic efficiency of batteries [29, 30, 55, 86].

As depicted in Figure 9, microstructural defects, such as grain boundaries or voids, within the solid electrolyte become localized points of current concentration, serving as the primary paths for dendrite growth and electrolyte destruction [63, 65, 85].

3.2.2 | Solutions: Artificial Solid-Electrolyte Interphase (SEI) and Pressure Control

Research efforts are being directed toward the creation of artificial SEIs, such as LiF or Li_3N , on the lithium surface to suppress

dendrites, as well as the coating of lithium-friendly metals (gold (Au) or Ag) to promote uniform electrodeposition [55, 73, 75, 76]. From a material perspective, the application of amorphous or glassy solid electrolytes without grain boundaries can also be effective. This strategy fundamentally blocks grain-boundary paths that could lead to dendrite growth and promotes uniform ion conductivity distribution [33, 35, 36].

Furthermore, pressure control technology, which involves applying external pressures on the order of several megapascals to maintain interfacial contact by accommodating lithium volume changes during charge and discharge, is being developed. This technology is considered crucial for uniform lithium plating and stripping [28, 32, 87]. Additionally, the utilization of a “3D host” to accommodate the infinite volume expansion of lithium metal is attracting attention [29, 30, 74]. Storing lithium within a 3D structure, such as porous carbon or metal foam, not only suppresses dendrite growth by dispersing lithium nucleation sites but also minimizes macroscopic volume changes of the electrode during charge and discharge, thereby preventing contact loss with the solid electrolyte [29, 30, 74].

3.3 | Emerging Anode Technologies

3.3.1 | Silicon Anode: Managing Volume Expansion

Silicon anodes, which are attracting attention as an alternative to Li-metal, can achieve high capacities (4200 mAh/g) but undergo >300% volume expansion during charging [3, 4, 22, 26]. To overcome this drawback, structural designs that mitigate volume changes and maintain anode–electrolyte contact by incorporating nano-sized silicon particles or silicon-porous carbon composites are being studied [3, 4, 26].

3.3.2 | Lithium–Indium (Li–In) Alloy: Benchmark for Laboratory Research

Aside from the development of high-capacity materials for commercialization, Li–In alloys play a crucial role in laboratory-level fundamental research [5, 48]. Li–In alloys have a stable operating potential of ~0.6 V (vs. Li/Li^+), suppress lithium dendrite growth, and exhibit low overvoltage characteristics [5]. Hence, they are widely used as “half-cell” reference electrodes for evaluating the inherent performance of anodes or solid electrolytes, eliminating interfering variables on the cathode side [5, 48].

3.3.3 | Ag–C Nanocomposite and Anode-Free Concepts

Recently, anode-free technology utilizing Ag–C nanocomposite layers has emerged as an innovative solution [88, 89]. Pioneered

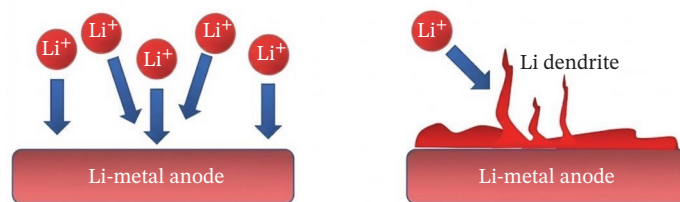


FIGURE 9 | Schematic illustrating mechanisms of lithium dendrite growth through grain boundaries and voids in solid electrolytes. Reprinted with permission from Moradi et al. [7], Copyright 2023, Elsevier.

by Samsung Electronics and others, this technology involves initially assembling batteries without anode active materials before inducing even lithium deposition between the current collector and the Ag–C layer during charging [88]. It is considered one of the technologies closest to commercialization, as it can suppress lithium dendrite growth effectively while dramatically increasing energy density [88, 89].

4 | Manufacturing Processes and Advanced Characterization

Commercializing ASSBs will require the establishment of manufacturing processes capable of producing large-area cells with laboratory-level performance, as well as advanced analytical technologies capable of elucidating the complex phenomena occurring at solid interfaces. This section discusses the future trajectory of manufacturing processes for mass production, along with next-generation analytical and data-science technologies that can accelerate material design.

4.1 | Fabrication Processes

4.1.1 | Pellet and Thin-Film Processes: Fundamental Studies and Niche Applications

Pellet and thin-film processes are primarily utilized in the early stages of ASSB research or for special purposes. The pellet process involves placing electrolyte and electrode powders in a mold and compressing them at pressures exceeding tens of megapascals to create a single-layer cell. This simple process is ideal for rapidly evaluating the unique electrochemical properties of materials [3, 13]. However, the large cell thickness and difficulties in large-scale production limit its use in commercial cell manufacturing [3, 13]. By contrast, the thin-film process involves producing a uniform electrolyte film several micrometers thick through vacuum deposition procedures (sputtering, atomic layer deposition, etc.) [35, 36]. This method minimizes the ion diffusion distance, thereby lowering the internal resistance and enabling the formation of fine patterns; hence, it is used to fabricate power sources for ultrasmall medical devices or micro-electromechanical system sensors [35, 36]. However, it is unsuitable for the mass production of large-scale energy storage devices, such as EV batteries, due to the high process cost and low deposition rate [35, 36].

4.1.2 | Sheet-Type Process: Toward Mass Production and Dry Processing

To enable the commercialization of large-scale ASSBs for EVs, a sheet-type process that can utilize the roll-to-roll infrastructure of existing LIB manufacturing facilities is essential [13, 16]. The current mainstream wet-slurry process involves mixing electrolyte, binder, and solvent and coating the mixture onto a current collector or support; hence, it is advantageous for continuous, large-area production [16, 102]. However, sulfide-based electrolytes are susceptible to reacting with polar solvents, which renders the selection of non-polar solvents and binder optimization crucial [13, 44].

Recently, dry processes have emerged as an innovative alternative that can fundamentally eliminate the side effects and drying

process costs associated with solvent use [13, 16]. Dry processes involve mixing electrode/electrolyte powders with a fiberizable binder, such as polytetrafluoroethylene, to form a film without a solvent. This process prevents chemical degradation of the electrolyte and affords high electrode density [13]. Thus, it is considered a key technology that can dramatically reduce production costs through process simplification.

Furthermore, for mass production, process innovations such as (i) low-temperature sintering, which densifies the electrolyte at temperatures below 200°C; (ii) rapid sintering, such as spark plasma sintering (SPS), which applies current to rapidly form dense structures; and (iii) ultraprecision slot-die technology, which ensures uniform thickness even during high-speed coating, must be implemented in parallel [16, 68, 69].

4.1.3 | Cell Stacking and Packaging Strategies

Apart from manufacturing unit cells, stacking and packaging technologies for configuring them into high-voltage, high-capacity modules are also important [3, 6]. Since ASSBs do not contain liquid electrolytes, they facilitate the implementation of a bipolar structure that allows for series connections within the cell, which can substantially increase the volumetric energy density of the battery pack [4, 48]. However, a highly reliable sealing process using aluminum pouches or other suitable components is essential for protecting moisture-sensitive materials, such as sulfide-based batteries; moreover, a mechanical pressurization design that can transmit uniform pressure between the stacked cells within the pack must be implemented [4, 12, 102].

4.2 | Advanced Characterization Techniques

Advanced analytical techniques with capabilities surpassing those of conventional methods are required to elucidate the subtle chemical reactions and mechanical defects occurring at solid–solid interfaces [9, 37].

Figure 10 summarizes the primary interfacial defects that cause performance degradation in ASSBs. Phenomena such as micro-cracking, debonding, and element interdiffusion depicted in the Figure 10 occur deep within the cell, which complicates nondestructive testing [9, 37, 96]. Therefore, precise analysis techniques, such as X-ray photoelectron spectroscopy and transmission electron microscopy (TEM), have been essential for elucidating the origin and propagation of these defects at the atomic level [9, 37].

Specifically, the recent introduction of cryo-TEM technology has enabled the atomic-level observation of electron beam-sensitive Li-metal and organic interfaces without causing damage [9, 29]. Conventional TEM analysis is problematic in that the energy of the electron beam can cause lithium dendrites to melt or deform. However, cryo-TEM, which rapidly cools samples to below –170°C, allows for complete imaging of the initial growth behavior of lithium dendrites and the original structure of the SEI [9, 29]. This is crucial for visualizing the dendrite growth mechanism and verifying the effectiveness of the interfacial protective layer [9, 29, 62]. Furthermore, 3D tomography using a field-infrared scanning electron microscope contributes to the understanding of mechanical failure behaviors by highlighting the pore distribution and crack propagation paths within the electrode

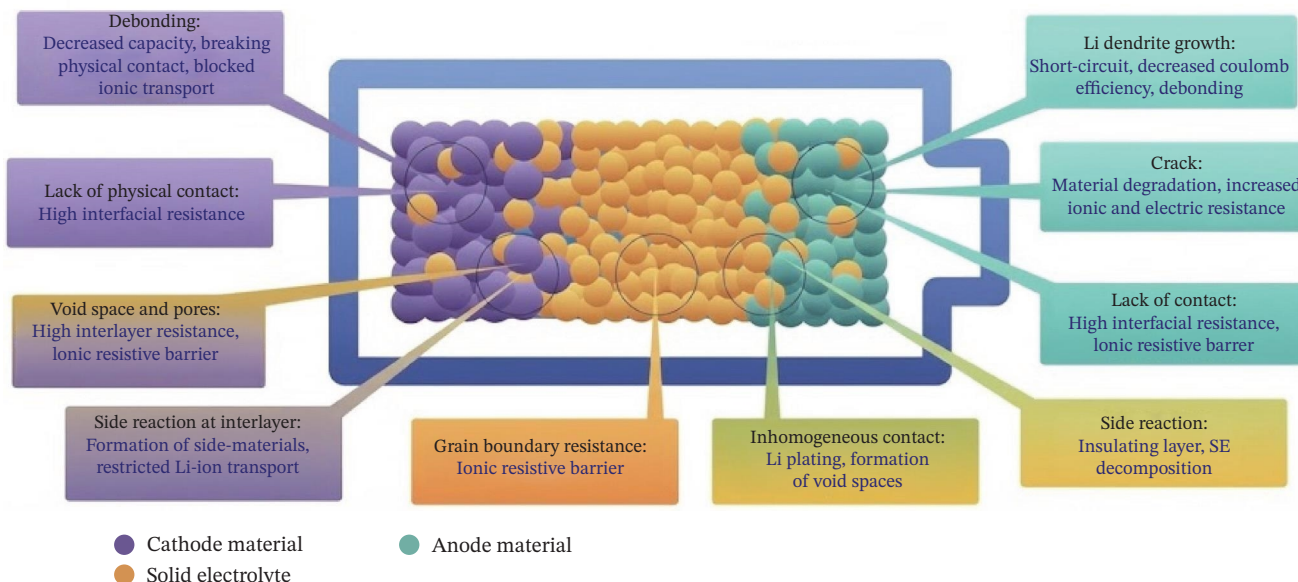


FIGURE 10 | Interface-related challenges with ASSBs: mechanisms, impacts, and mitigation strategies. Reprinted with permission from Moradi et al. [7], Copyright 2023, Elsevier.

[9, 62]. Moreover, time-of-flight secondary-ion mass spectrometry (TOF-SIMS) is utilized to track the movement of lithium ions and variations in their distribution during battery operation. TOF-SIMS can precisely map the lithium concentration distribution (depth profiling) in the depth direction of the electrode and the electrolyte cross-section, providing key data for observing the concentration or depletion of lithium at specific interfaces during charge and discharge [9, 94].

4.3 | Data-Driven Material Design

To maximize the efficiency of ASSB material development, data-driven design, which combines artificial intelligence (AI) and machine learning (ML), is being increasingly utilized [17, 27]. As tens of thousands of combinations of solid electrolyte and electrode materials exist, experimentally verifying the interfacial stability and ionic conductivity of each combination would be extremely time-consuming and expensive [17, 39]. Therefore, high-throughput screening techniques are gaining attention as a feasible solution [17, 27]. Specifically, by utilizing a massive materials database built through first-principles computation (i.e., density functional theory), ML algorithms are trained to predict the properties of unknown materials and identify promising candidates [17, 27]. For example, AI can be used to screen for optimal halide compositions that simultaneously deliver high ionic conductivity and a wide potential window from among thousands of lithium-ion-conductor candidates, or to recommend coating materials exhibiting the lowest reactivity with a specific cathode material [17, 19, 28]. Extending beyond simple material exploration, this approach helps minimize experimental trial and error and drastically shortens the material development cycle by predicting element diffusion behaviors at solid interfaces as well as SCL formation [17, 39, 91].

5 | Strategies for Commercialization

To move beyond the laboratory and enter the actual EV and ESS markets, ASSBs must first achieve technological maturity, as well

as economic feasibility and system-level reliability [3, 4]. This section analyzes cost reduction strategies, system integration design, and the development roadmaps of major companies for ASSB commercialization.

5.1 | Cost Analysis and Mass Production

5.1.1 | Material Costs and Processing Challenges

The most significant barriers to the commercialization of ASSBs are high material and manufacturing costs. Sulfide-based solid electrolytes (e.g., $\text{Li}_6\text{PS}_5\text{Cl}$), currently the main research focus, utilize high-purity Li_2S and P_2S_5 as raw materials that must undergo complex synthesis processes; thus, their per kilogram prices are tens of times those of existing liquid electrolytes [6, 13]. Furthermore, as sulfide and halide materials are extremely sensitive to moisture, the entire manufacturing process—from raw-material synthesis to electrode fabrication and cell assembly—must be performed in a dry-room or an inert atmosphere with a dew point of -40°C or lower. This necessitates significant infrastructural investments and incurs substantial operating costs [6, 13].

5.1.2 | Cost Reduction Strategies

In terms of materials, research is underway to alleviate manufacturing-related environmental constraints by utilizing sodium (Na)-based solid electrolytes instead of the expensive lithium or introducing highly air-stable phosphate-based glass electrolytes [13, 15]. In terms of process, simplifying processing steps and saving energy by replacing high-energy sintering techniques with solution-based synthesis or cold-press technology is essential [16, 19]. Recently, a process has been proposed in which an electrolyte precursor solution is directly impregnated into the electrode and then solidified in situ. This method is attracting attention as a cost-effective alternative because it can yield dense electrolyte layers without a separate sintering process [13, 16].

5.2 | System Integration: Pack and Battery Management Systems (BMSs)

5.2.1 | Mechanical Pressure Management

ASSBs suffer from a high risk of loosening or delamination of the solid interface due to volume changes in the Li-metal or active material during charging and discharging. Therefore, a mechanical design that maintains a uniform stack pressure of several megapascals is essential, not only for single cells but also for modules and packs [5, 87]. This necessitates system technology that integrates pressure-cushioning pads or spring mechanisms within the pack to maintain consistent surface pressure even under long-term driving vibrations or thermal expansion/contraction [87].

5.2.2 | Thermal Management and Advanced BMSs

While ASSBs carry minimal risk of thermal runaway, their sensitivity to temperature-dependent internal resistance changes necessitates a sophisticated thermal management system. Specifically, the output may drop sharply at low temperatures due to the reduction in ionic conductivity, and local resistance heating may occur; therefore, a heating and cooling system that maintains the temperature of the entire pack evenly is important [15, 28]. In fact, the output of ASSBs drops at temperatures below -10°C due to the rapid reduction in the solid electrolyte's ionic conductivity, whereas the battery lifespan is shortened due to the accelerated side reactions between the electrolyte and the electrodes at temperatures above 60°C [28]. Therefore, an active thermal management algorithm is essential for ensuring a wide operating temperature range. Additionally, distinct from those of existing LIBs, a BMS algorithm specialized for ASSBs that can precisely diagnose the state of charge and state of health based on the voltage behavior and resistance change characteristics must be developed in parallel [15, 28].

5.3 | Industry Trends and Roadmap

5.3.1 | Global Development Status

Global battery manufacturers and automakers are pursuing commercialization along different technological paths. Samsung SDI is seeking to solve the dendrite growth problem and maximize energy density by leveraging its proprietary Ag-C nanocomposite layer cathode design with a sulfide-based electrolyte; the company is currently operating a pilot line and targets mass production by 2027. SK On is focusing its capabilities on developing pouch-type cells that utilize halide-based electrolytes, which are advantageous for dendrite suppression, in addition to polymer-oxide composite electrolytes [19]. LG Energy Solution is following a two-track approach—polymer-based technology that can utilize existing LIB processes, combined with sulfide-based technology to achieve high output—and is focusing on securing mass production through low-temperature sintering processes [13, 15]. QuantumScape (United States of America) has demonstrated a fast-charging system that combines an oxide-based electrolyte with a Li-metal cathode, while Solid Power is attempting to reduce initial investment costs by adopting a sulfide-based sheet process compatible with existing LIB manufacturing lines [6, 13]. Toyota (Japan) is focusing on developing a durable, hybrid ASSB, intended for commercialization in 2027–2028 [15].

5.3.2 | Commercialization Roadmap

According to industry consensus, the commercialization of ASSBs is expected to proceed in stages [5, 15].

5.3.2.1 | Short-Term (Until 2025). This represents a material performance optimization and small-cell demonstration phase. The focus will be on securing high-conductivity electrolytes and interface stabilization technologies.

5.3.2.2 | Medium-Term (2025–2030). This will be a pilot production and initial commercialization phase. Manufacturing processes for large-area cells will be established, and limited deployment in premium EV models will begin. The target cell energy density will be 350–400 Wh/kg [5].

5.3.2.3 | Long-Term (2030 and Beyond). This will be a full-scale mass production and popularization phase. Price competitiveness will be secured through process cost reductions and supply chain stabilization. By achieving ultrahigh-energy densities of >500 Wh/kg, ASSBs will be expected to become mainstream in the EV market [5, 16].

6 | Conclusion

ASSBs represent next-generation ESSs that can overcome the fundamental flammability and energy-density limitations of conventional LIBs, which positions them as a key technology that will revolutionize the EV and ESS markets. This review article thoroughly analyzed ASSB commercialization from an integrated perspective encompassing electrolyte materials, interface engineering, manufacturing processes, and system-level integration. The main contribution of this review is its systematic connection of material-level limitations with interfacial degradation, scalable processing, and commercialization requirements.

From a materials perspective, no single solid electrolyte currently satisfies all requirements for practical ASSBs, including high ionic conductivity, wide electrochemical stability, mechanical deformability, moisture stability, low cost, and process compatibility. Sulfide-based electrolytes provide high ionic conductivity and processability but suffer from moisture sensitivity and high-voltage instability. Oxide-based electrolytes offer excellent chemical stability but require high-temperature processing and exhibit poor interfacial contact. Polymer-based electrolytes are attractive for flexible processing but remain limited by low room-temperature ionic conductivity and weak dendrite suppression. Halide-based electrolytes have recently emerged as particularly promising materials because they can partially reconcile the stability-conductivity-processability trade-off. Their compatibility with high-voltage cathodes, potential to reduce or simplify protective coating processes, and relatively mild processing conditions make them attractive for high-energy ASSBs and scalable cathode composite design.

Interface degradation remains one of the most critical barriers to ASSB commercialization. The formation of SCLs, interfacial decomposition products, lithium dendrites, dead lithium, micro-cracks, and contact loss increases internal resistance and accelerates capacity fading. These degradation phenomena are not

independent but are strongly coupled during repeated cycling; therefore, chemical stabilization alone is insufficient for long-term operation. Future research should focus on integrated interface designs that simultaneously control chemical stability, mechanical integrity, and ion/electron transport. Dynamic self-healing interfaces, single-crystal cathodes, artificial SEIs, dual-electrolyte architectures, and halide-based composite cathodes should therefore be further investigated under practical operating conditions using advanced characterization methods such as cryo-TEM and TOF-SIMS.

From a manufacturing and commercialization perspective, the transition from laboratory-scale pellet cells to large-area commercial cells remains a major challenge. Dry processing, sheet-type fabrication, low-temperature densification, SPS, and solution-based halide SSE synthesis offer promising routes for reducing process complexity, solvent-related degradation, and production energy consumption. However, scalable production still requires further optimization of electrode uniformity, electrolyte densification, binder compatibility, moisture control, defect tolerance, and reproducibility during continuous large-area manufacturing. In addition, ASSB-specific pack design, pressure management, thermal control, and BMS algorithms must be developed because ASSB performance is strongly affected by stack pressure, temperature-dependent ionic conductivity, and solid–solid interfacial resistance.

In conclusion, ASSBs are no longer merely laboratory-scale concepts but emerging industrial battery systems. Future studies should establish standardized evaluation protocols based on realistic conditions, including high areal capacity, lean electrolyte content, practical stack pressure, wide temperature ranges, long-term cycling, and large-format cells. If the remaining challenges in electrolyte design, interface stabilization, scalable manufacturing, cost reduction, and system integration are resolved, ASSBs can become a key platform for next-generation high-safety and high-energy-density batteries. Accordingly, the future development of ASSBs should be directed toward an integrated commercialization framework that connects materials design, interface engineering, process scalability, and intelligent system management.

Nomenclature

PEO:	Polyethylene oxide
EV:	Electric vehicle
PVDF:	Polyvinylidene fluoride
ESS:	Energy storage system
NASICON:	Sodium super ionic conductor
LIB:	Lithium-ion battery
SEI:	Solid-electrolyte interphase
ASSB:	All-solid-state battery
SPS:	Spark plasma sintering
NMC:	LiNixMnyCo _z O ₂
TEM:	Transmission electron microscopy
LCO:	LiCoO ₂

TOF-SIMS:	Time-of-flight secondary-ion mass spectrometry
LLZO:	Li ₇ La ₃ Zr ₂ O ₁₂
AI:	Artificial intelligence
ESW:	Electrochemical stability window
ML:	Machine learning
LGPS:	Li ₁₀ GeP ₂ S ₁₂
BMS:	Battery management system
SCL:	Space charge layer.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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