Review Article

Solid-State Battery TechnologyforGrid Stability and Energy Storage Applications

Abstract

Herein we reviewed solid-state batteries (SSBs) as an emerging and promising alternative to conventional lithium-ion batteries, offering enhanced energy density, safety, and longevity. This paper explores the potential of SSBs to revolutionize grid stability and energy storage. The unique characteristics of SSBs, including their solid-stateelectrolytes (SSEs) and absence of liquid components, significantly mitigate safety concerns associated with traditional batteries. Moreover, SSBs exhibit higher energy density and faster charging rates, making them ideal for applications demanding high energy storage capacity and rapid response times. The paper further discusses the key challenges and advancements in SSB development, including material selection, manufacturing processes, and cost reduction. It also highlights the anode and cathode materials but also the interface challenges faced during the design and development of SSBs. By addressing the limitations of current energy storage solutions, SSBs offer a promising pathwaytowarda more resilient and sustainable energy future.

Keywords: solid-state batteries, energy storage, electrolytes, cathode, anode.

1.0 INTRODUCTION

Due to the rising requirement for reliable and efficient energy storage, research is comparing solid-state and lithium-ion batteries. The current industry standard, lithium-ion batteries, has altered several sectors, from electric cars to portable electronics, due to its long lifetime and high energy density. However, safety, energy capacity, and scalability issues have driven research into alternate methods.These concerns may be solved with solid-state batteries (SSBs). By replacing lithium-ion batteries' solid electrolyteswith liquid or gel electrolytes, solid-state batteries may increase energy density, safety, and longevity.

Energy storage is essential for our endeavors to utilize renewable sources of energy, remediate greenhouse gases, and develop a stable power system [1,2]. Given the rapid global concern of migrating to cheap energy sources, it is important to comprehensively investigate and assess the working mechanism of battery technologies that facilitate this transformation [3].

Nevertheless, the progress of SSBs has faced significant obstacles [4]. These challenges primarily include: i.) the absence of suitable solid-stateelectrolytes (SSEs) that possess high ionic conductivity, a broad electrochemical range, appropriate mechanical stability, and practical applicability on a large scale; ii.) substantial interfacial resistance that restricts the transport kinetics of ions and electrons across interfaces; and iii.) a scarcity of manufacturing processes and technologies that can effectively produce viable SSBs [5].

These achievements signify that the world is moving towards a new age of digitization and automation, in response to the needformore efficient energy sources. A crucial element of developing sustainable energy sources is the application of materials that produce zero emissions[6]. By the Paris Agreement [7], significant nations have committed to limiting the increase in the Earth's average temperature to less than 2 °C. The International Energy Agency (IEA) has projected that a minimum of 20% of road cars should be powered by green energy sources by 2030, according to the United Nations Framework Convention on Climate Change (UNFCCC) in 2015. The capacity of renewable electricity is projected to increase by 50% from 2019 to 2024, with Solar Photo Voltaic (PV) systems leading the way [8]. Renewable energy sources depend on energy storage systems, and there is a growing focus on battery development due to the changing energy landscape. A battery is a device that contains one or more electrochemical cells that convert chemical energy into electrical energy. Batteries are widely prevalent and ubiquitous, yet their growth and popularity as energy sources have been hindered by various concerns such as safety, availability, cheapness, and charging/discharging rate [9]. These problems have hindered the progress of battery technology in comparison to the advancements in electronic gadgets. This study examines several battery technologies aboutkey metrics such as density, efficiency, material properties, cost, safety, and other important factors for sustainable and reusable energy sources. This review seeks to determine if solid-state batteries are on the verge of becoming the next major advancement in energy storage, or whether lithium-ion technology will maintain its dominance in the market [10].

1.1 HISTORY

According to Keyser [11], the Parthians developed battery technology 2000 years ago. They were able to produce 1-2 volts of electric power using a galvanic cell composed of an iron rod and clay enclosed in a copper tube filled with vinegar as a solution. In 1800 AD, Alessandro Volta, the discoverer of an early modern battery, observed that some fluids may provide a continuous flow of electric power when utilized as conductors. Table 1 enumerates other significant advancements in battery technology. At first, the batteries were created utilizing commonly accessible and well-liked anode and cathode materials.

Table 1.OVERVIEW OF CHANGES IN BATTERY TECHNOLOGIES.

Duration	**Technology**
1836 AD	Development of a primary cell (Daniel Cell).
1860 AD	The leadacid battery also known as a secondary cell was designed [12]
1866 AD	Thedesignof the Leclanche cell
1886 AD	First dry cell using Zinc Carbon Cell(a variant of Leclanche cell)
1991 AD	DevelopmentLithium-ion battery (LIB) by John B. Goodenough

Nevertheless, due to the scientific advancements in the fields of nanoscience, battery technology has seen gradual evolution via the use of novel materials. The use of renewable energy sources and the implementation of battery technology for energy storage in urban power networks provide a novel and sustainable option to address the challenges posed by energy crises, swings in energy production, and unpredictable power supply [13]. Batteries are often used as electrical energy storage (EES) systems in electrical grids to balance the load by storing energy and supplying it during periods of energy scarcity or increasing demand [14]. Although LIB technologies have reached a state of maturity, there is still considerable potential for the advancement of group (c) battery technologies. This is attributed tothe progress in nanomaterial production, namely the fabrication of graphenes and MXenes. Based on the latest research conducted by Mckinesy [15], the combined worldwide value of lithium, cobalt, and nickel for batteries is expected to be over $5 billion. Cobalt accounts for around 60% of this value, while lithium makes up around 30%, and extremely Nickel in its pure form represents approximately 10%. Additionally, the decline in performance of LIB may be attributed to diminished power output or lower discharge capacity at low temperatures, as well as excessive use and aging.

The many battery technologies that are now accessible may be classified into three main classes, as described inTable 2. Out of the many battery technologies that have been available for many years, the use of lithium-ion batteries (LIB) accounted for 88% of 2016, according to the International Energy Agency (IEA)[8] and Kala[16]. The shifting pattern of battery technologies groups (a) and (b) demonstrates the growing dominance of LIB, which is gradually displacing other battery technologies. This may be attributed to LIB's lightweight nature and its superior oxidation potential.

Table 2: Different classes of batteries[16]**.**

Class	Type	Examples	
Group (a)	Primary Cell	Carbon /Zinc	Li/SOCl$_2$
	Secondary Cell	NiCd	LIB
	Flow battery	ZnBr	ZnCl
Group (b)	Dry Cell	NiMH	NiCd
	Alkaline battery	Zn/MNO$_2$	BaSO$_4$-Zn/MNO$_2$
Group (c)	Pure Metals	Carbon /Zinc	NiMH
	Compounds/ Composites	LIB	Li$_{15}$Si4
	Nanomaterials	Ti$_3$C$_2$T$_X$ (MXene)	Ti$_3$CNT$_X$(MXene)

LIBshavegood energy densities and have been applied in portable devices and electric cars thus setting the standard for energy storage devices. Nevertheless, to ensure a more elaborate and thorough analysis, we dive into the lesser-knownyet equally promising technologies that have carved out their ~~own~~ distinct areas of expertise within the industry [7]. Lead-acid batteries have a well-established track record in automotive and grid storage, and they offer reliable and cheap solutions. Current studies have reinvigorated their ability, bringing them back to the center of attention. Flow battery technologies are widely recognized for their versatile and flexible nature to be expanded to storelarge quantities of energy and for use in grid-related functions. These technologies represent a significant shift in our viewpoint regarding storage devices. The ability to discharge and efficiently store energy, combined with their enduring lifespan, renders them an interesting object of study. Sodium-ion batteries, a new development in the area, provide the possibility of eco-friendly energy storage by utilizing sodium-based materials.

2.0 TYPES OF BATTERIES

1. 1. Lithium-Ion Batteries: These have brought about a significant transformation in the portable electronic devices and automotive sectors. Lithium materials function as active components in both electrodes of these batteries. LIBs offer numerous benefits, such as long-lifecycles, high energy density, and low self-discharging rates [17]. Furthermore, they offerstrong power output, fast charging speeds, and impressive energy performance. Unlike other types of batteries, Li-ion batteries are highly sensitive to temperature fluctuations and are equipped with complex safety features to prevent uncontrolled overheating. Recent developments in Li-ion battery technology have resulted in energy densities reaching as high as 250 Wh/kg and cycle lifetimes exceeding 10,000 cycles [18].
2. Lead-acid batteries have found application in-carsystems, uninterruptible power supply (UPS), and stationary energy storage. The batteries have lead and lead oxide electrodes that are immersed in a sulfuric acid electrolyte solution. Lead-acid batteries have several benefits, such as being inexpensive, reliable, and having a large capacity for sudden increases in current flow [19]. Nevertheless, they possess drawbacks such as a restricted number of cycles, lower energy density in comparison to other technologies, and the need for regular maintenance.
3. Flow batteries employ external tanks to store energy by containing electrolyte solutions. The structure consists of two distinct electrolyte streams that are separated by a membrane. Electrolytes traverse electrochemical cells while in operation, producing electricity via redox reactions. Flow batteries have several advantages, including the

capability to enhance capacity, extended longevity, and rapid reaction times [20]. They are particularly suitable for energy storage on a large scale and for applications at the grid level. Conversely, flow batteries exhibit lower energy density compared to other technologies, need more physical space, and demand intricate system design. Flow battery technology has made significant progress, with energy densities over 30 Wh/L and cycle durations beyond 5000 cycles[21].

4. Nickel-cadmium(NiCd) batteries have also found wideapplicationssuch as in portable devices, cordless power tools, and emergency backup systems. NiCd batteries exhibit a wide range of operating temperatures, demonstrate strong performance in challenging environments, possess a high tolerance for overcharging and deep draining, and have a long lifespan of charge-discharge cycles. However, NiCd batteries have some limitations, such as a "memory effect" that might reduce their capacity when they are repeatedly partially discharged. Furthermore, they possess harmful cadmium, a poisonous substance that poses a threat to the environment and necessitates proper recycling and disposal procedures [22].
5. Nickel-Metal Hydride (NiMH) Batteries: NiMH batteries arehighly reliable compared to NiCd batteries due to their higher energy density and less environmental effect. Since the negative electrode of NiMH batteries is made of an alloy that absorbs hydrogen rather than hazardous cadmium, they are considered ecologically benign. About NiCd batteries, NiMH batteries offer longer cycle lives, a higher energy density, and a lower chance of memory effect. However, they show faster rates of self-discharge and greater sensitivity to high temperatures [23].

3.0 SOLID-STATEBATTERIES

Lithium ions are moved more easily between electrodes in lithium-ionbatteries by using a liquid electrolyte, namely from the cathode to the anode. Stored energy is converted into usable electrical energy by the electrolyte, which makes it easier for electrical charge to move between the two terminals. Instead of using a liquid electrolyte, solid-state batteries combine a solid electrolyte with a lithium metal anode. The alternative way of increasing the energy density of the battery is to use lithium metal as the anode instead of graphite. However, since it promotes the growth of lithium dendrites, using regular liquid electrolyte in conjunction with a lithium metal anode is not practical. This potentially dangerous event might lead to short circuits and decreased battery capacity, among other battery degradation issues. Under automotive operating circumstances, several solid-state electrolytes canlower the likelihood of lithium dendrite growth and formation[24].

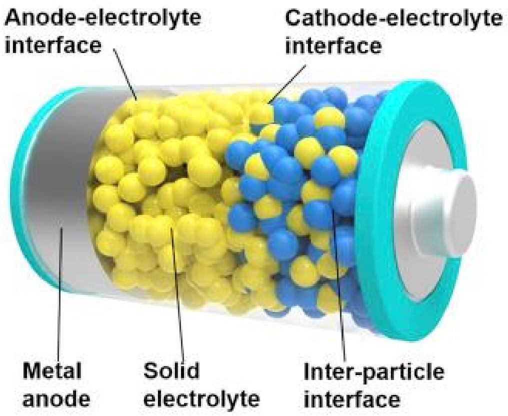

Fig 1: Schematic of Different Interfaces in Solid-State Batteries [25].

4.0 SOLID-STATE ELECTROLYTE

Several solid-state electrolytes (SSEs) using different anion chemistries such as S^{2-}, O^{2-}, and X^{-} (where X represents F, Cl, Br, and I) have beenextensively studied as core materials for solid-state batteries in recent decades. These SSEs include anti-perovskite-,solid polymer-,halide-, sulfide-, oxide-, and borohydride-based electrolytes. Every kind of SSE has its advantages and disadvantages. For example, sulfide electrolytes, namely Li9.54Si1.74P1.44S11.7Cl0.3, have a high ionic conductivity of 25 mS.cm^{-1} at room temperature. However, these electrolytes have the drawback of being unstable in air and releasing poisonous gas (H_2S) when in contact with thesurroundings. However, the prices of these electrolytes are still much below the level that meets industrial demands. Hence, it is essential to enhance air stability and decrease the cost of sulfide electrolytes as fundamental requirements for advancing their SSB technology. On the other hand, oxide electrolytes have advantageous air stability, a high ionic conductivity of 1 mS.cm-1, and a broad range of electrochemical windows. However, the device integration of oxide electrolytes is limited due to their high elastic modulus [26].Up to now, oxide electrolytes have been effectively used in the creation of quasi-solid-state batteries, either in combination with liquid electrolytes or gel polymer electrolytes. The typical oxide electrolyte, $Li_7La_3Zr_2O_{12}$, is susceptible to chemical reactions with water and carbon dioxide. This leads to the production of Li_2CO_2 and LiOH on the surface of the electrolyte, causing a reduction in the compatibility with lithium ions (low interfacial lithiophilicity) [27]. Electrolytes containing Borohydride have favorable ionic conductivity; yet, their limited temperature stability and proneness to hydrogen (H_2) release raise concerns over their practical use. The stability of anti-perovskite electrolytes against lithium metal is exceptional, while their ionic conductivity at ambient conditions requires enhancement [28].When it comes to the mechanical qualities of SSEs, electrolytes from solid-state polymers are regarded as the most practical option for producing batteries on a large scale, even if their ionic conductivity at room temperature (about 10-6 $S.cm^{-1}$) is not adequate. Bolloré has successfully commercialized a 30 kWh lithium metal polymer (LMP) battery, which has been put into their Bluecar. This battery allows the Bluecar to have a driving distance of 250 km in urban usage and a maximum velocity of 120 kmh^{-1}. Recently, there have been numerous reports on solid-state halide electrolytes. These electrolytes have shown high ionic conductivity (> 1 $mS.cm^{-1}$), high oxidation stability (> 4 V against Li^+/Li), and favorable mechanical softness (likesulfide electrolytes) [29,30,31]. Wet chemistry techniques were developed by a research group for producing halide electrolytes and conducted a comprehensive analysis of their structure-to-property correlation [30,31,32].Zhou et al.[33] showed that SSBs using a halide electrolyte ($Li_2In_1/3Sc_1/3Cl_4$) have excellent high-voltage stability (> 4.8 V vs Li^+ /Li) and long-term cycle stability. Despite the exceptional electrochemical performance of halide-based SSBs, they nevertheless face significant challenges becauseoftheir susceptibility to moisture and their instability when used with next-generation anodes, such as Li metal. Furthermore, it is crucial to create inexpensive halide electrolytes that have a high atomic efficiency. Although many solid-state electrolytes have been created using different anion chemistries, there is still a need for a flawless SSE that meets all the requirements of solid-state batteries. Hence, it is vital to always strive to strengthen the current SSEs and cultivate inventive alternatives. Furthermore, it is crucial to explore the research avenue of creating composite solid-state electrolytes that integrate the benefits of both inorganic and organic materials [26]. Meanwhile, researchers in this area are advised to get a thorough understanding of the link between the structure and properties of solid-state electrolytes by the use of first-principles calculations and sophisticated characterization methods. This will provide detailed insights into the mechanism of ion transport and the crystal structure of SSEs.

4.1 DESIGN COMPONENTS OF IDEAL SOLID-STATEBATTERIES

The best SSE for SSB applications has not yet been discovered, since the existing technologies suffer significant interfacial problems. Lithium dendrite-penetrating SSEs, point-to-point solid-solid ionic contact resulting in inadequate ionic contact, harmful interfacial interactions, and physical contact loss due to active material volume changes during charge/discharge are some of these difficulties. The interfacial challenges posed by SSBs are discussed in this part, along with some promising solutions and predictions for the anode and cathode, respectively, in the future [10].

4.1.1 CATHODE MATERIALS FOR SOLID-STATEBATTERIES

The effect of space-charge at the cathode interface is a widely recognized phenomenon that impedes the flow of charges due to the electrochemical potential difference between the cathode and solid-state electrolyte. Utilizing a buffer layer as a dielectric at the contact can significantly lower the influence of the space charge effect [34]. Furthermore, the interaction of the cathode active materials (CAMs) and SSEs results in the creation of a resistive interfacial layer. This layer significantly hinders the flow of ions and electrons across the interface. It is highly desirable to have a coating layer at the interface that exhibits a high level of ionic conductivity, as this helps prevent reactions on the cathode side. However, there is a notable lack of understanding regarding the rational design of optimal interfacial coating materials, specifically in terms of their ionic conductivity, mechanical characteristics, and electronic conductivity. One significant barrier that causes the loss of physical contact is the change in the volume of the electrode materials. Although external pressure can help tacklethese issues, it may not be very feasible to apply significant pressure in real-world scenarios. Introducing wet agents is an effective remedy. However, it is important to carefully evaluate the chemical reactiveness between the wet agent and the other components in the composite. In addition, the inclusion of conductive carbon is typically required to ensure continuous pathways for electron movement in electrode composites. However, these substances that conduct electrons can also cause the degradation of solid-state electrolytes, particularly in the presence of sulfide electrolytes. Therefore, it is essential to establish a balanced equilibrium between electron and ionmigration at the electrode composite interface to create solid-state batteries (SSBs) that possess both high power density and extended cycle life. $LiCoO_2$ and high-nickel (Ni) cathodes are the main focus of research for solid-state batteries (SSBs). To address concerns regarding cobalt resources, it is crucial to accelerate the development of cobalt-free cathodes. Moreover, it is crucial to further the progress of cathodes that have high storage capacities, such as those made of sulfur and oxygen. Advanced techniques like, synchrotron analysis, cryo-TEM, high-resolution transmission electron microscopy (TEM)and distribution of relaxation time (DRT) [35] are important for understanding the degradation mechanism at the interface and the kinetics of charge transport across the interface.

4.1.2 ANODE MATERIALS FOR SOLID STATE BATTERIES.

The anode interface of most solid-state electrolytes may be easily reduced when combined with a lithium metal electrode. This is because theelectrochemical potential of the lithium anode is the lowest, which is -3.04 V, compared to the conventional hydrogen electrode (SHE). To tackle this problem, interfacial coatings have been designed to inhibit any unwanted side effects. Li dendrites are commonly encountered in solid-state batteries, resembling a liquid system. This phenomenon is likely due to inadequate solid-solid contact at the interface, the electrical conductivity of solid-state electrolytes ranging from 10^{-10} to 10^{-8} $S.cm^{-1}$, the presence of spaces, and the formation of bulk defects and random surfacesduring SSE preparation [26]. There are a few effective methods to prevent the formation of Li dendrites. One approach is to create a Li host material that allows for easy movement of Li ions, such as using alloy anodes. Another method is to provide a wetting agent at the interface, which helps control the way Li is deposited. This information is based on a study by Zhao et al. [36]. However, Li/SSE/Li symmetrical cells are often evaluated with a very restricted areal capacity of 0.1-0.5 $mA.h.cm^{-2}$, which is not feasible for actual applications [34]. Certain lithium solid-state electrolyte (Li/SSE/Li) cells have exhibited an exceptionally high critical current density (CCD), beyond which lithium dendrites can breach the SSE layer and result in short circuits. The existing test technique for CCD consistently operates at a level that is below the minimum capacity, and so should be reevaluated. Furthermore, the majority of prior research has relied on dense lithium metal, which is obtained from real-world uses. Subsequent research should employ a slender lithium layer, such as one measuring 30 micrometers. Due to substantial volume fluctuations during cycling, it is very important to develop sophisticated methods to handle the volume variation of a thin Li metal anode. While the utilization of a Li metal anode greatly enhances the energy density of SSBs, it is imperative to thoroughly determine the safety of solid-state lithium metal batteries [37]. In addition to Li metal, it is necessary to simultaneously develop alternative anode materials, such as silicon,graphite, Si/C, and alloys (e.g., tin (Sn), for SSB devices[38]. Anode-free solid-state batteries represent a viable avenue, as exemplified by Samsung, despite the significant obstacles they pose [39].

4.2 INTERFACIAL CHALLENGES FOR FULL CELL DEVELOPMENT

Unlike conventional lithium-ion batteries (LIBs), solid-state batteries do not rely on a liquid electrolyte to facilitate the movement of lithium ions between the cathode and anode. Instead, SSBs need precise contact between the different materials and components that are supposed to be physical. The specifications for the interfaces are succinctly described as: i) Close contact with less resistance to lithium transfer, ii) Stable interfaces to enhance battery longevity. Within the context of SSB, one may see many interfaces where solid materials and components meetone another. The primary interface at the anode is between the lithium metal and the SE. If the SE is a composite material, additional interfaces may emerge. At the cathode, someinterfaces coexist, including thosebetween the conductive additive, CAM, and the SE, the interface between the current collector and the cathode, and the CAM (and/or the SE) which is also significant. Redesigning and adapting the manufacturing chain of batteries to solid-state technology is crucial, considering the cohabitation of many interfaces and their respective physical characteristics [10]

4.3 COMPOSITE SOLID CATHODES AT THE INTERFACES

Cell integration results in numerous interfaces at the level of cell components, such as the electrode and electrolyte, as well as at the level of the composite electrode, such as the CAM and electrolyte, and the current collector and electrolyte material. Issues due to interfaces are responsible for a significant portion of the challenges faced in the process of achieving an SSB. Inadequate contact is a significant cause of charge buildup and hindersthemovement of mass between electrode materials, solid electrolytes, and current collectors. Maximizing the contact area between theion-conductive phase, CAM and electron-conductive phase might boost performance in certain situations. Nevertheless, the expansion and contraction of the cathode particles, known as volume changes, that occur during electrochemical cycling, along with the electrochemical and thermal stability of the electrolyte and electrode materials, are significant factors contributing to the increase in cell impedance and ultimately the failure of the cell [10].

4.4 MECHANICAL INTERFACIAL CHALLENGES

During electrochemicalcycling, mechanical stress is encountered by all electrode materials. The stress arises from the structural and volumetric changes that occur during the reversible extraction and insertion of Li-ion. The anisotropic cell parameter variation of common Li-ion cathode materials varies from 2% (e.g. between $LiCoO_2$ and $Li_{0.5}CoO_2$ in the c-direction) to over 5% (between $LiFePO_4$ and $FePO_4$ in a direction). This variation causes holes and disruption of contact at the interfaces between the cathode active material (CAM), electronic conducting material, and solid electrolyte (SE). Mechanical fatigue poses a hindrance to the movement of electrons and ions and has been linked to the decline in capacity and eventual failure of batteries [40,41,42]. The mechanical characteristics of the boundary between CAM and SE exhibit significant variations based on the selection of electrolytes. Ceramics with a high young modulus, such as oxides (>100 GPa), are prone to accumulating significant local stresses that may result in the fracture of the ceramic cathode. On the other hand, ceramics with ductile properties, such as sulfides (~20 GPa) [43], thiophosphates, or polymers (less than 1 GPa), are better able to mechanically support volume expansion.

The utilization of conductive additives is essential to prevent any loss of electronic contact, which is necessary for efficient electron collection and power density. These additives play a crucial role in maintaining electronic conductivity within the electrode, even when there are volume changes. However, it is important to note that they do not address the issue of ionic transport losses. Specifically, the use of conducting additives with a high aspect ratio, such as carbon fibers, helps to reduce the loss of electrical conduction between CAM particles and the current collector while the cell undergoes cycling [44].

More so, the size and shape of particles have a significant impact on both the density of the material and the surface contact between the components of a solid electrode. Reducing the size of the CAM particles enhances the surface properties available for interaction between the CAM, SE, and conductive additive [45]. Reducing the particle size diminishes the significance of mechanical stress and the extent of volume expansion per particle. External conditions: The mechanical integrity of the electrode and the entire cell can also be ensured by applying external forces, such as pressure, to the cell. Empirical evidence has specifically demonstrated this for polymer-based solid-state batteries and cells utilizing sulfide electrolytes [46,47]. Due to the flexible characteristics of these two materials, the consistent pressure aids in the rearrangement of the SE and ensures continuous and close contact with the CAM and conductive additive.

4.5 CHEMICAL AND ELECTROCHEMICAL CHALLENGES

Thermally inducedprocesses often cause side reactions at the interfacial, leading to elemental diffusion and potentially the creation of an interphase between a solid electrolyte and a cathode-anode material. The temperatures necessary for certain processes, which are influenced by the chosen electrolyte as mentioned earlier, will significantly affect the two materials stability chemically. As stated earlier, certain processing methods necessitate elevated temperatures to consolidate the materials and reduce interfacial resistance, especially for electrolytes based on oxides (high-temperaturesintering). The interaction between positive electrode materials and solid electrolytes can result in thermal deterioration, leading to the formation of new phases, often undesirable products. This can cause a significant increase in interfacial resistance, resulting in severe loss of electrochemical performance [48]. The chemical reactivity between the CAM and SEis observed even at room temperature [49]. This is because thetransition metal reduction favors the oxidation of the anion, which is beneficial for many cathode/conductor pairs [50,51,52]. Additionally, it is important to consider the reactivity between impurities that are deposited on the surface of the cathode and the solid electrolyte. For example, carbonates and other species areharmful in sulfide solid-state cells, as described by Visbal et al.[53]. Therefore, it is crucial to have a comprehensive knowledge of the thermodynamic and kinetic reactive pathways that occur between the cathode-anode material at various surface species, states of charge,and the electrolyte. This understanding is essential for accurately assessing the electrochemical performance of these systems. Furthermore, when exposed to the cathode potential, several SEs will undergo oxidation and transform into phases with reduced lithium concentration. PEO-based electrolytes have restricted oxidative capacities, of around 4 V [54]. In addition, it has been proposed that some cathode materials, such as $LiCoO_2$, which possess a high oxidizing capacity, promote the decomposition of PEO [52]. The inclusion of hydroxyl (-OH) groups may contribute to the reduced oxidative stability seen in electrolytes based on polyethylene oxide (PEO)[55]. Coordination of polymer electrolytes containing polymer chains with lithium salt may potentially reduce the oxidation potential of the chains compared to their original form. This is because theoxidized state containing the positive charge is shielded by the salt anion, as explained by Wang et al. [56]. The practical use of polyether electrolytes is mostly confined to cathodes in the 3 V-class, such as LFP. One way to address this issue is by using coated CAMs, such as $Li_{1.4}Al_{0.4}Ti_{1.6}(PO_4)_3$-coated $LiCoO_2$, which help protect PEO from oxidation [55]. Composite polymer electrolytes were shown to exhibit greater stability (>4 V) compared to polymer electrolytes without fillers. This was seen in particular with the use of LLZO [57] and $LiZr_2(PO_4)_3$[54] as fillers. The hindranceof anion breakdown can be due to the Lewis acid-base relationship between the salt and filler. This problem can also be addressed by utilizing alternate polymer hosts that have enhanced electrochemical stability. An instance of this is when polymer electrolytes, namely those derived from poly (ethylene ether carbonate), exhibited excellent cyclability at room temperature when used in conjunction with NMC622 as the cathode material with a cut-off voltage of 4.3 V [58]. When it comes to inorganic compounds, the maximum level of oxidation is mostly influenced by the chemistry of the anions. Among these compounds, fluorides have the greatest oxidation limits, followed by chlorides, polyanionic oxides, and non-polyanionic oxides [59,49]. Sulfides have the smallest range of electrochemical stability and undergo oxidation above 2–2.5 V. On the other hand, LATP and LAGP have the highest predicted oxidation stability, exceeding 4 V [60]. Reactions due to electrochemical processes will take place anywhere the solid electrolyte (SE) comes into contact with the route of electrons, such as the current collector or conductive additive. LiPON is an unusual case where the electrochemical breakdown products at both low and high voltage act as insulators for electricity. This leads to the formation of stable layers that prevent further reactions and allow for the flow of ions [60]. To create a solid-state cell, it is necessary to carefully select the right materials and processing procedures. This is important to guarantee that the material remains chemically and electrochemically stable, and to prevent the formation of breakdown products at the interfaces of composite cathodes. The decomposition products must demonstrate inadequate electronic transport to prevent ongoing decomposition.

5.0 CONCLUSION

SSBs have become widely popular worldwide due to their excellent safety features and remarkable energy density. However, solid-state batteries face significant challenges in terms of materials, interfaces, and overall cell performance. It is important to continuously explore solid-state electrolytes (SSEs) that exhibit high ionic conductivity, broad electrochemical stability, excellent chemical stability, and can be produced on a large scale at the material level. In addition, it is advised to employ multidisciplinary theoretical calculations and characterization techniques, such as material selection based on machine learning, to determine the most suitable solid-state electrolyte (SSE) and gain a thorough comprehension of its ion transport mechanism. To achieve rapid kinetics and long-term stability, it is necessary to customize interfacial charge transfer at the interface level. Understanding the failure process is crucial for improving interface techniques. Research is currently being carried out to improve the electrochemical performance of solid-state batteries at the cellular level. While acknowledging the significance of this, it is equally crucial to simultaneously focus on developing inexpensive and high-throughput fabrication methods that can facilitate the mass production of SSBs. Moreover, conducting a thorough examination of SSBs, including their self-discharge characteristics, thermal durability, dependence on pressure, and financial viability, is essential for their effective implementation in the market.

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data and materials

Not applicable.

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