ISSN Number: 2454-2024(Online)

International Journal of Technical Research & Science

A NOVEL APPROACH TOWARDS SOLID-STATE BATTERY TECHNOLOGY

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Abstract– Batteries play a vital role in modern life, powering everything from household appliances and electronic gadgets to medical equipment and electric vehicles. Beyond these everyday applications, batteries are increasingly recognized as a cornerstone of future energy systems, particularly for stabilizing electrical grids that rely on intermittent renewable sources such as wind and solar. Among the various battery technologies, solid-state batteries (SSBs) have recently gained significant attention due to their unique advantages over conventional lithium-ion systems. By employing solid electrolytes, SSBs deliver higher energy and power density, improved safety, and extended lifespan. These features make them highly suitable for electric mobility, grid-scale storage, and other advanced applications. This paper explores the different types of solid-state batteries, highlights their advantages, and discusses the research challenges and future prospects of this emerging technology.

Keywords: Solid-state batteries, Solid electrolytes, Energy storage, Electric vehicles, Smart grid, Battery safety, High energy density, Renewable integration.

1. INTRODUCTION

Solid State Batteries harness more stable solid electrolytes to replace the volatile and flammable liquid electrolytes in traditional Lithium-ion batteries. The rapid development of LIB technology and the continuous expansion of the market have put great pressure on battery safety, and broad attention from the public can be expected once a battery-related accident occurs. Battery-related accidents, especially in emerging applications such as EVs and energy storage, have been increasing in recent years. Moreover, the scale of such accidents increases significantly with the increase in battery capacity. Researchers and engineers have proposed numerous methods to handle the safety issues of LIBs from the perspectives of intrinsic, passive, and active safety; among these methods, the development of solid-state batteries (SSBs) has great potential for covering all three types of safety strategies. Europe, Japan, the United States, and the Republic of Korea have launched national projects to support the research and development (R&D) of SSBs, including Battery 2030+ in Europe, RISING3 and Solid-EV in Japan, Battery500 in the United States, and K-Battery 2030 in the Republic of Korea. Different types of SSBs, such as sulfide-, oxide-, thin-film-, and polymer-based batteries, are being developed at the same time. It is very important to strengthen both the fundamental scientific research and the applied research related to the safety of SSBs to facilitate the maturity of SSB technology and eventually establish a market.

2. TYPES OF SSBs

Solid State Batteries are classified into various categories based on the solid electrolyte material used:

2.1 Polymer Solid Electrolyte

Polymer electrolytes are widely used in electrochemical devices. They have a high molecular weight membrane and are easier to process. The properties of polymer electrolytes include transparency, lightweight, highly flexible, increased ionic conductivity, wide range in the electrochemical window, and low fabrication cost. Polymer electrolytes are further classified into gel polymer and all solid-state polymer electrolytes. A gel-based polymer consisting of a polymer matrix typically in the form of a gel holds a liquid electrolyte; this unique combination provides stability and superior conductivity. It has an enhanced safety profile, and is less corrosive, reducing the risk of leakage of damage. Solid polymer electrolyte also known as solvent-free polymer electrolyte is a pure solid electrolyte without liquid components it's key functionality lies in the coordination of inorganic salt within a polymer matrix. It has low conductivity at room temperature and is more suitable for working in high temperatures.

2.2 Oxide Solid Electrolyte

Oxide solid electrolytes can be subdivided into crystal state and glass state (amorphous). Crystalline electrolytes, also known as conductive ceramics, include perovskite-type, Na Super Ionic Conductors type, Li Super Ionic Conductors type, and garnet type. Perovskite type has high electrochemical oxidation voltage but is resistant to heat flow which serves as a drawback. These electrolytes have high strength, high hardness, and high chemical stability and they are also stable in the air.

DOI Number: https://doi.org/10.30780/IJTRS.V11.I02.001

2.3 Solid Electrolyte

Similar to oxide inorganic electrolyte but has a larger ionic radius and stronger polarization than oxide electrolyte hence it can increase lattice volume and expand the size of lithium-ion channels. In addition, it has an increased concentration of carriers and exhibits greater ionic conductivity. Its key characteristics include easy operation, resistance to thermal conductivity, highly flexible and can withstand a sufficient range of stress and strain, and highly conductive. Limitations of Sulphide electrolytes include poor compatibility, sensitivity to moisture, and can easily form oxides and peroxides.

3. ADVANTAGES OF SSBs

3.1 Safety

The most important incentive for implementing solid-state batteries is their improved safety relative to conventional Lithium-ion batteries. The liquid electrolytes are flammable and if damaged can lead to them catching fire and can even explode. Solid electrolyte provides a solution to this since it is not flammable. Moreover, it can reduce the dendrite growth of Lithium ions to a certain degree.

3.2 Durability

Electrolyte decomposition and electrode side reaction are the main factors affecting battery life. The presence of solid electrolytes can reduce the tendency to decompose the electrolyte through an electrochemical process. Besides, solid electrolytes can improve battery life by inhibiting side reactions on electrodes. This results in a longer lifetime of the batteries which is highly desirable for several applications including automotive.

3.3 Higher Power and Energy Density

Power density is a measurement of how fast batteries can provide stored energy. Solid electrolytes have a higher potential to increase power density. With the continuous development of new materials, a large number of solid electrolytes with high ionic conductivity are being discovered. They give solid-state batteries a big breakthrough in power density and make the solid-state battery reach a high power density comparable to lithium-ion batteries. Also to keep up with demanding energy storage applications, lighter and smaller batteries with higher energy densities are required. SSBs have great potential in delivering high energy density as well.

3.4 Faster Charging Time

Faster charging times are highly desirable to EV consumers. The charging rate of current lithium-ion automotive batteries is fundamentally limited by the cell chemistry as well as the engineering required to protect the battery from exposure to high temperatures. SSEs have close to unity lithium-ion transference numbers and, in theory, negligible concentration polarisation, and higher thermal conductivity compared to liquid electrolytes. These properties should allow SSEs to transport lithium ions efficiently with adequate dissipation of heat and therefore may be a route to faster charging automotive battery systems.

3.5 Larger Electrochemical Window

The chemical window refers to the potential difference between oxidation and reduction reactions. Both electrodes must be inert to electrolytes. This means that the oxidation potential needs to be higher than the lithium-ion embedding potential in the cathode, and the reduction potential must be lower than the lithium metal potential in the anode. Generally, solid electrolytes can withstand higher electrochemical windows which are around 4-5 V. Therefore, solid electrolytes are more compatible with more electrode materials.

4. RESEARCH CHALLENGES

Solid-state batteries still have multiple challenges to overcome. The main challenge is to overcome dendrite formation. These tree-like structures grow on the Li-metal anode, promote degradation, and ultimately grow to the opposite electrode resulting in a short circuit. Another major challenge in solid-state batteries is contact loss, solids have a definite shape and when voids are present in the structure, the solid can not flow into the void as easily as liquids, which results in contact loss. Additionally, during battery operation electrode particles expand or shrink during cycling and can lose contact with the electrolyte. Besides contact loss, interphase formation is one of the main challenges. Interphases are formed at the active material/electrolyte interface, which, in battery literature, is often referred to as the solid electrolyte interphase or SEI. In this interphase layer, Li-ion diffusion is often sluggish which limits the performance of the battery.

5. DEVELOPMENT AND FUTURE POTENTIAL

5.1 Wave 1 in the 2020s: Consumer electronics, healthcare, and wearables

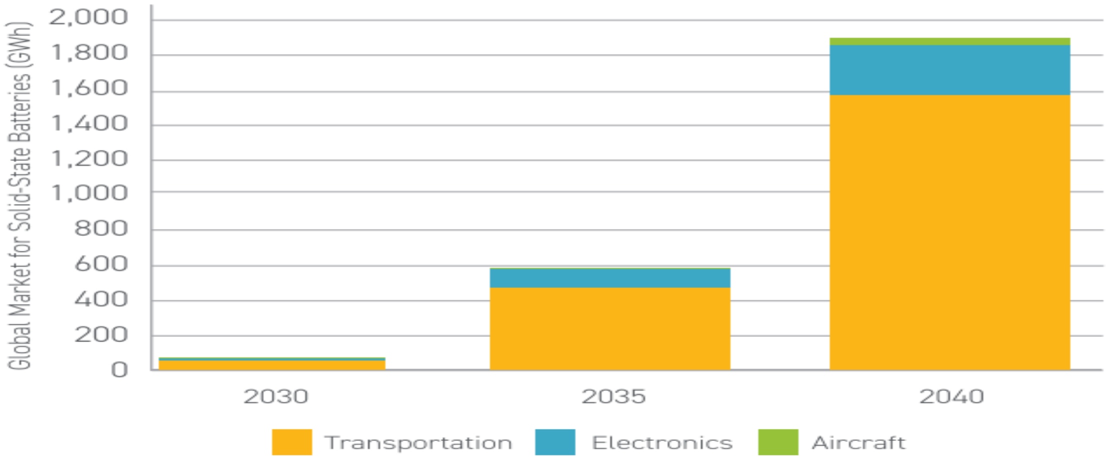
Small healthcare products and niche electronics are already available and smaller applications in consumer electronics and wearables have hit the mass market around 2022 (e.g. Ilika). Barriers to entry are low as the size of batteries required are very small. Consumer products are replaced frequently, so do not require a long lifecycle. One of the most promising technologies for use in extremely hot and cold temperature environments. Its ability to charge relatively quickly is also important for viable consumer products.

5.2 Wave 2 in the 2030s: Electric Vehicles

In this period, the safety issue of flammability in lithium-ion batteries will be addressed. Increased energy density of SSBs will deliver significant improvements in EV range and the issue of range anxiety will be addressed. Commercial SSBs are already available in EVs (e.g. Blue Solutions) but need to operate at above room temperature. This period would be too early to compare the performance, safety, and cost of SSB EVs with current EV models with liquid electrolytes.

5.3 Wave 3 in the 2040s: Aircraft and Aviation

This period will witness a leap forward in performance leading to large-scale roll-out across the aviation industry. Aircraft are heavy and aviation requires substantial amounts of energy. SSBs will likely be introduced initially for smaller/narrow-body aircraft, helicopters, and hybrid technologies, initially in the 2030s but with a wider roll-out in the 2040s. SSBs could be used in new concepts such as vertical take-off and landing for applications in urban transport. Initial application to commercial aviation is unlikely for 20+ years given long manufacturing lead times in aerospace.



Source: The Faraday Institution / various web sources

Fig. 5.1 Global annual SSB GWh demand by application to 2040

CONCLUSION

SSBs have the potential to significantly improve safety, thereby reducing the need for additional safety measures. With advanced cell design SSBs are a feasible technological route to achieve both high power and energy density and high safety. In the future, all solid-state batteries will break through technology and production bottlenecks. With the continuous improvement of battery material performance, solid-state batteries will improve further in terms of energy density and safety. Eventually, solid-state batteries will be industrialized and become one of the essential energy storage tools for future development.

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