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Advancing Solid-State Batteries with Nanomaterials: Enhancing Safety, Performance, and Energy Efficiency

Junbo Lang [1, *]

[1]Nanjing No.13 middle school international department, Nanjing, Jiangsu, 210029, China

Abstract. Solid-state batteries (SSBs) are a promising advancement in energy storage technology, offering higher energy density and improved safety compared to traditional lithium-ion batteries. The integration of nanomaterials into SSBs has the potential to overcome key technical challenges, including low ion conductivity, interface instability, and mechanical failures. This review explores the role of nanomaterials in enhancing the performance of SSBs by improving ion transport, stabilizing interfaces, and inhibiting dendritic crystal growth. Additionally, the application of nanoscale coatings on electrodes and solid electrolytes is discussed as a strategy to further optimize battery performance. While nanomaterials significantly improve the safety, efficiency, and longevity of SSBs, challenges such as large-scale production, cost control, and long-term stability remain. Continued research and innovation are essential to fully unlock the potential of nanomaterials in SSBs, which hold significant promise for sustainable energy storage solutions, particularly in electric vehicles and renewable energy systems.

1 Introduction

Solid-state batteries represent a promising advancement in battery technology, utilizing solid electrodes and solid electrolytes, as opposed to the liquid electrolytes found in traditional lithium-ion batteries. A key distinction between solid-state and conventional lithium-ion batteries lies in the replacement of the liquid electrolyte and diaphragm with solid electrolytes. Solid-state batteries typically offer higher energy density but lower power density. Given the widely held view that lithium-ion technology has reached its theoretical limits, solid-state batteries are increasingly seen as the next evolutionary step in energy storage, especially in applications where safety, performance, and energy efficiency are paramount.[*]

In evaluating battery technologies, researchers focus on key factors such as safety, performance, and energy efficiency. Safety and performance are particularly critical in electric vehicles (EVs) and portable electronic devices, where they directly impact user experience. The range, charging time, and power output of EVs are influenced by battery performance—higher energy densities result in longer ranges, faster charging reduces downtime, and high-performance batteries enhance power output. These metrics are essential

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[*]Corresponding author: lang2007@ldy.edu.rs

for the market competitiveness of EVs. Similarly, in portable electronics, batteries with extended lifespans and fast-charging capabilities greatly enhance user satisfaction.

Consequently, improving the safety and performance of batteries is essential for advancing EVs and portable electronics. The integrhold of nanomaterials into solid-state batteries holds significant promise for enhancing their performance. Nanomaterials applied to solid-state electrolytes and electrodes can significantly improve ion conductivity by optimizing the lithium-ion transport pathways, thereby increasing overall ion mobility. Additionally, nanomaterials contribute to the enhancement of interface stability between solid electrolytes and electrodes, which is crucial for maintaining long-term battery performance. By inhibiting the formation of dendritic crystals, nanomaterials mitigate the risk of short circuits, thus enhancing battery safety. Moreover, the inclusion of nanomaterials can strengthen the mechanical properties of solid electrolytes, improving their toughness and durability, which are critical for the longevity and reliability of the battery system.

This review aims to explore the utilization of nanomaterials in solid-state batteries to advance their safety, performance, and energy efficiency. It will address both the opportunities and challenges associated with nanomaterial applications, providing a comprehensive analysis of future trends and commercialization prospects. In particular, the review will consider the potential of nanomaterial-enhanced solid-state batteries to revolutionize sustainable energy storage and clean transportation, highlighting the transformative impact these technologies could have on the energy sector.

2 Technical overviews of solid-state battery

Solid-state batteries are composed of three key components: solid electrolytes, electrodes, and interfaces, each crucial to the battery's performance. The solid electrolyte serves as the core component responsible for ion transmission, replacing the liquid electrolytes used in traditional lithium-ion batteries. This transition to solid electrolytes significantly enhances the safety and stability of the battery, reducing the risks of leakage and combustion, which are common in conventional liquid electrolytes. The electrodes—comprising the positive and negative poles—are where the electrochemical reactions occur. The positive electrode typically contains lithium compounds, while the negative electrode can be made of lithium metal or other materials capable of absorbing and releasing lithium ions during charge and discharge cycles. Lastly, the interface—the contact point between the electrode and solid electrolyte—is essential for battery efficiency. Proper interface performance is critical to charge transfer and ion transport, as it directly influences the internal resistance and cycle life of the battery (Figure 1).

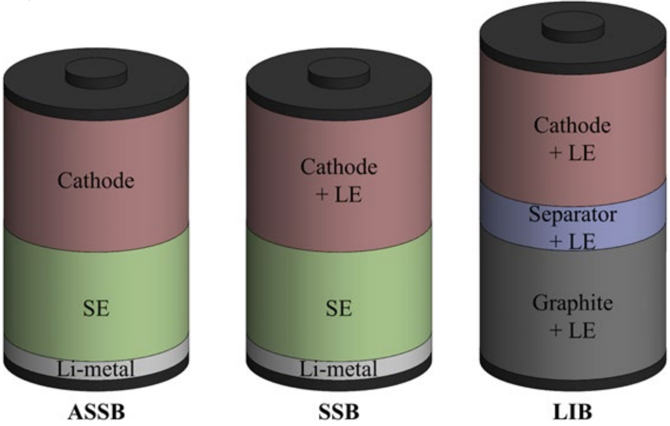

Fig. 1. Internal structure diagram of all-solid-state batteries, solid-state batteries and lithium-ion batteries [1]

A major distinction between solid-state batteries and all-solid-state batteries is the state of the electrolyte. While solid-state batteries may contain small amounts of liquid or gel electrolytes, all-solid-state batteries exclusively utilize solid electrolytes. This complete removal of liquid components improves safety by eliminating risks associated with leakage and combustion. Furthermore, all-solid-state batteries have the potential to achieve higher energy densities and longer cycle lives. However, they face significant technical challenges, including low ion conductivity in solid electrolytes and difficulties in maintaining stable interfaces between electrodes and electrolytes, which currently restrict the large-scale commercial application of all-solid-state batteries. As a result, solid-state batteries, which are somewhat less complex, are viewed as a transitional technology between conventional lithium-ion batteries and fully solid-state systems.

Compared to traditional lithium-ion batteries, solid-state batteries offer several important advantages. One of the most significant is improved safety, as the solid electrolyte reduces the risk of leakage, combustion, and other hazards associated with liquid electrolytes. This enhancement in safety makes solid-state batteries especially attractive for applications in electric vehicles (EVs) and portable electronic devices. Furthermore, higher energy density is another key benefit, as solid-state batteries can store more energy in a smaller space, extending the driving range of EVs and increasing the operational time of portable devices. Additionally, solid-state batteries are capable of operating effectively across a wider temperature range, making them more adaptable to various environmental conditions.

The introduction of nanomaterials into the development of solid-state batteries is viewed as essential to overcoming some of the key technical challenges associated with this technology. One major challenge is improving ion conductivity, which is a limiting factor in the performance of solid electrolytes. Nanomaterials can enhance the pathways for lithium-ion transport within the electrolyte, significantly increasing ion conductivity. For instance, the addition of LLZO ($Li_7La_3Zr_2O_{12}$) nanoparticles to solid electrolytes has been shown to boost ion transport and improve overall battery efficiency [2]. In addition to enhancing conductivity, nanomaterials can also play a pivotal role in stabilizing the interface between the solid electrolyte and electrodes. By incorporating polymer-based nanocomposites, the interface compatibility is improved, which reduces interface resistance and helps maintain long-term performance.

Another critical benefit of nanomaterials is their ability to inhibit the formation of dendritic crystals, which can cause short circuits in batteries, posing significant safety risks. Research shows that the introduction of ceramic nanoparticles can effectively suppress the growth of lithium dendrites, thus improving the safety and extending the cycle life of the battery [3]. Moreover, nanomaterials also improve the mechanical properties of solid electrolytes. The incorporation of materials such as nanofibers or nanoparticles into solid electrolytes enhances their mechanical strength and toughness, which increases the durability and reliability of the battery [3].

In conclusion, nanomaterials offer a promising solution to many of the technical challenges faced by solid-state batteries, including improving ion conductivity, stabilizing interfaces, inhibiting dendrite formation, and enhancing mechanical properties. These advancements not only enhance the safety and performance of solid-state batteries but also bring them closer to large-scale commercialization. As research continues, the integration of nanomaterials could play a key role in unlocking the full potential of solid-state battery technology, making it a cornerstone of future energy storage systems for applications ranging from electric vehicles to portable electronics.

3 Nanomaterials of solid electrolytes applied to solid-state batteries

3.1 Types of nanomaterials applied to solid electrolytes

Most researchers agree that the use of LLZO ($Li_7La_3Zr_2O_{12}$) solid electrolyte (SSE) in contact with the lithium metal anode can effectively reduce the formation of lithium dendrites, especially under the application of necessary pressure. This reduces the risk of short circuits and improves the battery's overall safety. However, the design of the cathode layer remains a topic of debate. Some researchers advocate for the addition of LLZO to the cathode, while others recommend using alternative electrolytes such as ionic liquids or polymers. This ongoing debate highlights the complexity of achieving the ideal configuration for lithium garnet solid-state batteries. For instance, the study by Kravchyk, K.V., Karabay, D.T., and Kovalenko, M.V. evaluates the feasibility of an all-solid-state battery using LLZO as the single electrolyte. Their analysis confirms the viability of such a configuration concerning achievable energy and power densities, as shown in Figure 2.

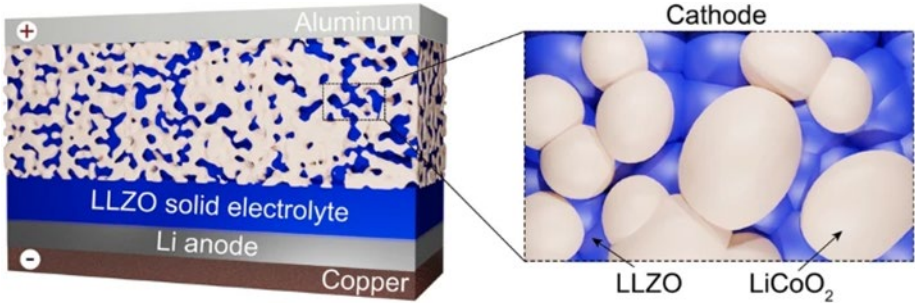

Fig. 2. Schematics of Li-garnet solid-state battery and solid-state cathode considered in this work for assessing the power and energy densities of Li-garnet SSBs [2].

In addition to LLZO, $Li_{1.5}Al_{0.5}Ge_{1.5}P_3O_{12}$ (LAGP) has also emerged as a promising material for solid-state battery applications. Recent research proposes a robust technique that involves smoothing the LAGP ceramic pellet to achieve a mirror-like surface. This method has demonstrated the capability to run a solid-state battery for an unprecedented 1,000 cycles with a capacity retention of 80% at 0.5C and 50 °C [4]. Both LLZO and LAGP are ceramic nanoparticles, and their inclusion in solid electrolytes contributes to the improved performance and longevity of solid-state batteries. Additionally, advances in polymer-based nanocomposites have shown significant potential, especially in lithium metal and "beyond lithium" (e.g., Na, K, Zn, Mg, Al) polymer-based batteries. These developments underscore the importance of ongoing research into diverse materials and configurations to enhance the performance of solid-state batteries.

3.2 The advantages of nanomaterials as solid electrolytes

Pure inorganic solid-state electrolytes (SSEs) are known for their high ionic conductivity, but they also present several challenges, such as uneven lithium deposition, low mechanical flexibility, and poor interface contact. These issues often result in high interface impedance and mechanical failure in inorganic SSE-based solid-state batteries. Nanocrystalline-based inorganic SSEs offer a promising solution, as they typically have lower interface impedance and excellent cyclic stability due to their high specific surface area and shorter lithium diffusion paths. For example, Song and his collaborators developed a dense nano-solid electrolyte, $Na_3Zr_2Si_2PO_{12}$, by calcining a nano-level ZrO_2 precursor. The solid-state symmetrical battery assembled with this electrolyte exhibited low interface impedance, indicating improved performance [5]. Additionally, Cui's research team achieved a significant breakthrough by inducing self-organized heterogeneous nanocrystalline domains in the glass ceramic-based SSE Li_2S-P_2S_5, resulting in an ultra-high lithium conductivity of 13.2 mS cm^{-1} at room temperature [6].

Applying nanoscale coatings on the surface of inorganic solid electrolytes is another common strategy to address the poor interface contact between inorganic solid electrolytes and electrode materials. For instance, insufficient contact between the inorganic solid electrolyte and the lithium metal anode can lead to rapid increases in interface resistance and uneven current density distribution. This imbalance can cause irregular lithium deposition, ultimately leading to battery failure due to the formation of lithium dendrites. Wan et al. demonstrated that coating the oxide electrolyte $Li_{6.5}La_3Zr_{1.5}Ta_{0.5}O_{12}$ (LLZT) with a pro-lithium nanofilm of Ta2O5 significantly improved the stability and reduced the interface resistance when paired with a lithium metal anode [7].

Moreover, the presence of defects, such as grain boundaries, pores, and impurity phases in inorganic SSEs, can exacerbate uneven lithium deposition and promote the growth of lithium dendrites. To mitigate these issues, Wang and his colleagues proposed a nano-confinement strategy aimed at controlling the defect-free growth of $Li_{0.33}La_{0.55}TiO_3$ (LLTO) crystals. By eliminating structural defects, they were able to significantly enhance the cycling performance of the batteries [7]. These findings underscore the critical role of nanoscale engineering in addressing the limitations of inorganic SSEs, thereby improving the reliability and efficiency of solid-state batteries.

4 Nanomaterials in electrodes

Previous studies have demonstrated that the physicochemical properties and stability of the cathode and the cathode/solid electrolyte (SE) interface have a profound influence on the performance of solid-state batteries (SSBs) [8]. Nanomaterials, with their ultra-high specific surface area, offer a significant advantage by increasing the contact area between the active material and the electrolyte. This larger contact area provides more active sites for charge transfer at the interface, which in turn enhances the electrochemical reaction kinetics. However, the increased surface area also raises the risk of side reactions, which can negatively impact the long-term performance of the battery. For instance, Wolfgang G. Zeier and his colleagues discovered that an FeS2 cathode with an average particle size of 9.7 nm delivered the highest reversible capacity (760 mAh g^{-1}) and excellent rate performance due to its reduced size. However, the capacity degradation was severe, primarily due to increased interface side reactions [9].

To mitigate this issue, without sacrificing the high capacity of nanostructured cathodes, Linda F. Nazar's group introduced a charge transfer carrier, $LiVS_2$, and designed a core-shell nanostructure $LiVS_2@Li_2S$ cathode by synthesizing it on the surface of Li_2S nanotubes. This innovative design prevented direct contact between the active cathode Li_2S and the electrolyte $Li_{5.5}PS_{4.5}Cl_{1.5}$, thereby ensuring an ultra-long cycle life. The capacity retention rate was approximately 80% after 1,000 cycles, demonstrating the potential of this approach to extend battery life while maintaining performance.

Nanotechnology is also employed to protect lithium metal anodes in solid-state batteries, though the interface environment poses new challenges. The failure of solid-state lithium metal batteries is often due to the growth of lithium dendrites, which can be traced to contact failure between the lithium metal and solid electrolyte during the stripping and plating process. To address this, Jürgen Janek and his collaborators proposed a composite anode made of lithium metal and a 3D carbon nanotube (CNT) scaffold. This design maintains electrical contact between the lithium metal anode and the oxide electrolyte, $Li_{6.25}Al_{0.25}La_3Zr_2O_{12}$, thereby improving battery performance and mitigating dendrite growth [10].

One of the most promising applications of nanotechnology in SSBs is the development of functional nanoscale surface coatings for cathodes, a key step in moving from laboratory research to industrialization. The interface between the cathode and electrolyte is a critical area in SSBs, and surface coatings have emerged as an effective strategy to optimize this interface. By applying functional coatings, researchers aim to adjust the cathode/electrolyte interaction, minimize side reactions, and improve overall battery performance. In the subsequent sections, I will present experimental data to illustrate the effects of nanomaterial applications in this area, showcasing the promising advancements in interface optimization through nanotechnology.

5 Enhance safety and performance through nanomaterials

Nanomaterials significantly enhance the safety and performance of solid-state batteries by addressing critical challenges related to solid-state electrolytes (SSE), electrodes, and the interfaces between them. One of the key improvements' nanomaterials bring is the enhancement of ion conductivity. By incorporating nanoparticles such as LLZO into solid-state electrolytes, the lithium-ion transport pathways are optimized, leading to increased ion conductivity, which is essential for improving the overall efficiency of the battery. This advancement helps solid-state batteries achieve higher energy densities and better performance in various applications.

Another crucial benefit of nanomaterials is their ability to enhance interface stability. Polymer-based nanocomposites improve the compatibility between solid electrolytes and electrodes, which reduces interface resistance and ensures smoother charge transfer. This contributes to improved cycling stability and longevity of the battery, addressing one of the major challenges in solid-state battery technology. Additionally, the use of ceramic nanoparticles helps inhibit the formation of lithium dendrites, which are responsible for battery short circuits. By preventing dendrite growth, nanomaterials enhance the safety of the battery and extend its lifespan.

Nanomaterials also play a vital role in improving the mechanical properties of solid-state batteries. The inclusion of nanofibers or nanoparticles in the solid electrolyte enhances its mechanical strength and durability, making the battery more reliable, particularly in demanding applications. Furthermore, advanced designs, such as the lithium metal-3D carbon nanotube composite anode, help maintain electrical contact between the lithium metal anode and the electrolyte, preventing contact failure and improving battery performance.

Lastly, nanoscale surface coatings on the cathode provide an effective means of optimizing the interface between the cathode and the electrolyte. These coatings reduce side reactions, enhance charge transfer, and prevent electrolyte decomposition, leading to improved performance and longer cycle life for solid-state batteries. Overall, nanomaterials offer comprehensive solutions to the challenges of solid-state battery technology, significantly improving safety, efficiency, and reliability.

6 Challenges and future directions

Nanotechnology plays a pivotal role in electrochemical energy storage devices, particularly solid-state batteries (SSBs), due to the unique physicochemical properties offered by nanoscale materials. These properties, driven by the small size of nanomaterials, allow for significant improvements in the performance and interface characteristics of key materials in

SSBs. This paper reviews how structural and coated nanomaterials enhance the comprehensive performance of SSBs, focusing on improving ion conductivity, interface stability, and overall battery efficiency.

However, the large-scale production of nanomaterials for SSBs presents several challenges. The complexity of the production process, which requires precise control and specialized equipment, increases the difficulty and cost of mass production. Ensuring consistent quality is another hurdle, as even small variations in the production of nanomaterials can significantly impact the performance of batteries. Cost-effectiveness remains a crucial factor, as the high production costs associated with nanomaterials must be addressed to make them commercially viable for widespread use in SSBs.

Economic factors also influence the application of nanomaterials in commercial SSBs. A large initial investment is required to develop production facilities for nanomaterials, which can place a financial burden on companies. Additionally, the balance between cost and performance is critical nanomaterials must provide significant improvements in battery performance while keeping costs manageable to meet market demand. The success of commercial applications will also depend on the scale of production and market acceptance of SSBs, both of which are essential for driving demand.

Further research is necessary to ensure the long-term stability and reliability of nanomaterials in SSBs. This includes studying the aging mechanisms of nanomaterials to understand how they change over time during battery operation, which can help in developing strategies to extend their lifespan. Optimizing material design to improve the durability and stability of nanomaterials is also essential, as is conducting long-term testing and verification to ensure their reliability in practical applications.

In addition to technical and economic considerations, potential environmental and safety issues related to the use of nanomaterials must be addressed. It is important to conduct thorough safety assessments to ensure that nanomaterials used in battery production, use, and recycling do not pose risks to human health or the environment. Furthermore, the recycling and reuse of nanomaterials after the battery's lifecycle ends should be considered to minimize their environmental impact, making sustainability a critical aspect of future SSB development.

7 Conclusion

Nanomaterials play a critical role in enhancing the performance of SSBs. Their application improves ion conductivity, enhances interface stability, inhibits the formation of dendritic crystals, strengthens mechanical properties, protects lithium metal anodes, and optimizes interfaces. These enhancements contribute to the overall safety, efficiency, and longevity of SSBs, making them a promising technology for future energy storage solutions. Despite the significant advantages nanomaterials bring to SSBs, there are still challenges to be addressed. Issues such as large-scale production, cost control, and ensuring the long-term stability and reliability of nanomaterials must be resolved to fully realize their potential. Overcoming these challenges is essential for the successful commercialization of nanomaterial-reinforced solid-state batteries.

Continued research and innovation will be key to advancing the application of nanomaterials in SSBs. As the technology evolves, SSBs are expected to make a substantial impact on sustainable energy storage and clean transportation, improving the range and safety of electric vehicles, shortening charging times, and contributing to the broader transition away from fossil fuels. The development of SSBs will also promote the integration and utilization of renewable energy sources, aligning with global sustainable development goals. While nanotechnology has already offered promising solutions to many failure issues in SSBs, further research and investment are necessary to fully unlock its potential in creating high-energy, high-safety, and long-life batteries. The future of SSBs lies in these continued advancements, which will play a vital role in shaping the future of energy storage and sustainability.

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