Proceedings of CONF-FMCE 2025 Symposium: Semantic Communication for Media Compression and Transmission
DOI: 10.54254/2755-2721/2025.GL24431

Solid-State Electrolytes for Next-Generation Energy Storge: Progress, Challenges, and Future Dierctions

Dongming Liu

School of Materials and Chemical Engineering, Changji University, Changji, China
yjsc@cjc.edu.cn

Abstract. Solid-state batteries (SSBs) represent a highly promising solution for the next generation of energy storage systems, offering high energy density, superior safety performance, and a prolonged service life. The development of solid-state electrolyte (SSE) materials is particularly critical, as their high ionic conductivity and interface stability directly determine the overall performance of solid-state batteries. Therefore, we focus on the application of solid-state electrolyte materials in new energy vehicle batteries. This paper adopts the method of literature reading and analytical research to review the cutting-edge progress of various solid-state electrolyte materials in the field of new energy vehicle batteries, revealing their key potential in improving energy density, safety and cycle life. This study concludes that SSEs, including those with carbon nanomaterials, rare earth bromides, and composite structures, significantly enhance the energy density, safety, and cycle life of new energy vehicle batteries. However, further research is needed to address challenges like silicon anode volume expansion and lithium dendrite suppression, while future efforts should focus on high ionic conductivity materials, interface optimization, cost-effective manufacturing, and interdisciplinary collaboration to accelerate solid-state battery commercialization and sustainable development in the new energy vehicle sector.

Keywords: solid electrolyte, lithium dendrite, battery safety, new energy vehicles

1. Introduction

With the widespread application of new energy technologies, the development trend of comprehensive electrification of modern transportation is becoming increasingly clear, and the market has put forward higher requirements for power batteries. The ideal next-generation high-energy density battery should be capable of fully addressing the range anxiety and safety hazards of electric vehicles, while also facilitating the development of large electric vehicles, such as electric trucks and electric aircraft.[1]. However, the current lithium-ion battery system is still imperfect. Existing commercial lithium-ion batteries mostly use organic liquid electrolytes, which are flammable and volatile, making thermal runaway a serious safety hazard. In addition, the energy density under the liquid system has limited room for improvement, and it is difficult to match the next generation of high specific energy requirements. Solid-state batteries use solid electrolytes with strong stability to replace flammable and explosive organic electrolytes, and their application potential in the field of new energy vehicles cannot be ignored.

© 2025 The Authors. This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (https://creativecommons.org/licenses/by/4.0/).

DOI: 10.54254/2755-2721/2025.GL24431

The research of Devendran, A.[2] et al. shows that advanced material systems such as metal organic frameworks (MOFs) and covalent organic frameworks (COFs) exhibit excellent ion transport properties and mechanical stability, providing new ideas for the design of solid electrolyte membranes. Mashentseva[3] et al. summarized the application of carbon nanomaterial-based gel polymer electrolytes in supercapacitors and new batteries, pointing out that the introduction of materials such as carbon nanotubes or graphene can significantly improve the mechanical properties and electrochemical stability of the electrolyte. Xu Chen[4] pointed out that composite solid electrolytes composed of inorganic fillers and polymer matrices can effectively overcome problems such as interface instability and lithium dendrite growth.

However, the commercialization of solid-state batteries still faces many scientific and engineering challenges. Silicon-based anode materials have become one of the hot topics in solid-state battery research because they have extremely high theoretical specific capacity and can significantly improve battery energy density. However, their volume changes greatly during the charging and discharging process, which can easily cause material structure damage and affect battery cycle stability and life. At the same time, lithium dendrite growth is also a serious problem faced by solid-state battery applications. It may pierce the battery separator and cause a short circuit, seriously threatening battery safety[5-6].

This study systematically reviews the research status and applications of solid-state electrolyte materials, reveals the key role of current technological progress in breaking through the limitations of traditional liquid batteries, points out the research direction for the development of solid-state electrolytes, and provides some suggestions. This study contributes to a deeper understanding of the critical challenges and opportunities in solid-state battery development, thereby facilitating the advancement of this promising technology and accelerating the transition towards a more sustainable and electrified transportation future.

2. Current status of solid electrolyte research

2.1. Gel polymer electrolyte based on carbon nanomaterials

Carbon nanomaterial-based gel polymer electrolytes have shown broad application prospects in the field of energy storage device research and development due to their excellent flexibility and ionic conductivity[7]. A.A. Mashentseva et al.[3] summarized the application of such materials in supercapacitors and new batteries, and especially pointed out that the introduction of materials such as carbon nanotubes or graphene can significantly improve the mechanical properties and electrochemical stability of the electrolyte. Specifically, carbon nanotubes, with their unique one-dimensional tubular structure and high aspect ratio, provide excellent mechanical support to gel polymer electrolytes. This enables the electrolytes to maintain structural stability under external mechanical deformation, thereby preserving their outstanding ionic conductivity Graphene, with its two-dimensional planar structure and excellent electronic conductivity characteristics, can effectively promote the migration of ions in the electrolyte, reduce ion transfer resistance, and thus significantly improve electrochemical stability. Although the relevant technology is still in the laboratory stage, its potential value in the field of new energy vehicles has attracted widespread attention. The development of new energy vehicles has an urgent need for high-performance energy storage systems, and carbon nanomaterial-based gel polymer electrolytes are expected to meet this need. Its excellent performance can improve the energy density, charge and discharge efficiency and cycle life of batteries, thereby improving the range and power performance of new energy vehicles[8]. With the progression of research and the maturation of technology, these materials are

DOI: 10.54254/2755-2721/2025.GL24431

anticipated to play a pivotal role in the future development of the new energy vehicle industry, driving advancements towards enhanced performance, safety, and reliability.

2.2. Composite solid electrolyte

Composite solid electrolytes are becoming one of the core development directions of future all-solid-state batteries due to their ability to combine the advantages of multiple single materials. Xu Chen [4] pointed out that composite solid electrolytes composed of inorganic fillers and polymer matrices can effectively overcome problems such as interface instability and lithium dendrite growth. At present, by precisely controlling the proportion of each component in the composite system and the microstructure design, the ionic conductivity and electrochemical stability of the material have been successfully improved. These achievements have laid the foundation for further optimizing the performance of all-solid-state batteries, and also provided a more reliable technical option for the new energy vehicle field.

2.3. Solid electrolyte materials for lithium metal batteries

Solid electrolyte materials for lithium metal batteries are considered to be ideal candidates for the next generation of power batteries due to their high specific energy and safety characteristics. Zhao[9] conducted a comprehensive review of the research progress of this type of material in his study and elaborated on the performance of current solid electrolyte materials in detail. It is pointed out that although the ionic conductivity of this material has made significant progress at room temperature, reaching the level of 10-3 S/cm, the internal microcrack problem gradually becomes prominent during long cycles. This problem seriously affects the stability and service life of the material, thus limiting its large-scale application. To solve this problem, Yang et al. proposed an innovative strategy of combining inorganic solid electrolytes with organic materials. Inorganic solid electrolytes have high ion conductivity, while organic materials help to reduce interfacial impedance. This combination is expected to achieve both high ionic conductivity and low interfacial impedance [10]. The resulting composite material demonstrates significant potential under high-temperature conditions. In such environments, enhanced ionic activity and accelerated migration rates further augment the ionic conductivity of the composite. Once the problem of ion migration at room temperature is overcome, solid-state electrolyte materials will be able to meet the strict requirements of new energy vehicles for high energy density, long life and safety. It is expected to be rapidly promoted in the field of new energy vehicles, providing strong technical support for the development of electric vehicles and promoting the new energy vehicle industry to a new stage of development.

3. Challenges facing solid-state electrolytes

3.1. Silicon-based anode materials

Silicon-based negative electrode materials have become one of the hot topics in solid-state battery research because they have extremely high theoretical specific capacity and can significantly improve battery energy density. However, their volume changes greatly during the charging and discharging process, which can easily damage the material structure and affect the battery cycle stability and life [11]. The persistent issue of volume expansion in silicon-based anode materials, if unaddressed, may lead to significant performance degradation in solid-state batteries during

DOI: 10.54254/2755-2721/2025.GL24431

practical operation. This could prevent them from meeting the performance criteria, such as driving range, required for new energy vehicles, thereby impeding their commercial viability.

3.2. Lithium dendrite suppression

Lithium dendrite growth is also a serious problem faced by solid-state electrolyte applications. It may pierce the battery separator and cause a short circuit, seriously threatening battery safety. These problems are not only directly related to battery performance and safety, but also determine the future commercialization potential of solid-state batteries [12]. Studies have shown that lithium dendrites can not only cause internal short circuits in the battery, making the battery unable to work properly, but can also cause serious safety accidents such as thermal runaway [13]. Once thermal runaway occurs, a large amount of energy will be released, which may cause the battery to burn or even explode, causing great harm to the use environment and equipment.

4. Future development direction of solid electrolytes

Addressing the current research gaps, several promising directions merit further investigation. First, future research should focus on the development of novel solid electrolyte materials exhibiting higher ionic conductivity and an extended operating temperature range. This includes the exploration of functionalized electrolytes based on metal-organic frameworks (MOFs) or covalent organic frameworks (COFs) to ensure performance under diverse climatic conditions. Secondly, enhancing interface engineering is crucial. This involves optimizing the interface structure between solid electrolytes and electrodes to mitigate interfacial impedance and improve cyclic stability. Thirdly, the development of cost-effective and environmentally benign manufacturing processes should be prioritized to reduce reliance on scarce resources and minimize energy consumption during production. Fourthly, integrating in-situ characterization techniques with theoretical simulation methods will facilitate a deeper understanding of the kinetic mechanisms underlying lithium dendrite formation and its inhibition strategies, providing a theoretical foundation for the construction of efficient and stable solid-state batteries. Finally, fostering interdisciplinary collaboration is paramount to accelerating the transition of solid-state battery technology from the laboratory to the marketplace, leveraging expertise from diverse fields such as materials science, chemical engineering, and computational science. The advancement of these research directions will lay the foundation for the commercialization of solid-state batteries and inject strong impetus into the sustainable development of the new energy vehicle industry.

5. Conclusion

This paper reviews the cutting-edge progress of various solid electrolyte materials in the field of new energy vehicle batteries, revealing their key potential in improving energy density, safety and cycle life. Studies have shown that carbon nanomaterial-based gel polymer electrolytes provide a new idea for the development of high-performance flexible batteries with their excellent flexibility and non-combustion properties; rare earth bromide solid electrolyte materials have demonstrated the ability to operate stably under high-voltage environments with their high ionic conductivity and wide electrochemical window; composite solid electrolytes effectively alleviate the problems of interface instability and lithium dendrite growth by combining inorganic fillers with polymer matrices. In addition, the research on silicon-based negative electrode materials has opened up a path for high-capacity battery design, although its volume expansion problem still needs to be

DOI: 10.54254/2755-2721/2025.GL24431

further overcome. These achievements have jointly promoted the practical application of solid-state batteries in the field of new energy vehicles and laid a solid foundation for future technological breakthroughs.

References

[1] Shen, Y. B. , & Chen, L. W. (2020). High Energy Density Power Battery Material Electrochemistry. Science Bulletin, 65(S1), 117-126. https://doi. org/10. 1360/TB-2019-0517

[2] Devendran, A. , Shahmirzaee, M. , & Nagai, A. (2024). Recent Progress on Metal Organic Framework and Covalent Organic Framework Based Solid-State Electrolyte Membranes for Lithium Battery Applications. ChemElectroChem. https://doi. org/10. 1002/celc. 202300847

[3] A. A. Mashentseva, A. A. Almanov, A. N. Aimanov& A. M. Zhumabayev, (2023). Application of Gel Polymer Electrolytes Based on Carbon Nanomaterials for The Development of Energy Storage Devices-Mini Review. NNC RK Bulletin. http://doi. org/10. 52676/1729-7885-2023-2-33-42

[4] Xu C. . (2023). Research Progress of Composite Solid Electrolytes for Solid-State Lithium Batteries. Chinese and Foreign Energy.

[5] Zhang, C. , Wang, F. , Han, J. , Bai, S. , Tan, J. , Liu, J. -s. , & Li, F. (2021). Challenges and Recent Progress on Silicon-Based Anode Materials for Next-Generation Lithium-Ion Batteries. Small Structures. https://doi. org/10. 1002/sstr. 202100009

[6] Majeed, M. K. , Hussain, A. , Hussain, G. , Majeed, M. , Ashfaq, M. Z. , Iqbal, R. , & Saleem, A. (2024). Interfacial Engineering of Polymer Solid-State Lithium Battery Electrolytes and Li-Metal Anode: Current Status and Future Directions. Small. https://doi. org/10. 1002/smll. 202406357

[7] Azizighannad, S. , Wang, Z. , Siddiqui, Z. , Kumar, V. , & Mitra, S. (2021). Nano Carbon Doped Polyacrylamide Gel Electrolytes for High Performance Supercapacitors. Molecules, 26(9), 2631. https://doi. org/10. 3390/molecules26092631

[8] Zielińska, A. , Carreiró, F. , Oliveira, A. M. , Neves, A. , Pires, B. , Venkatesh, D. N. , Durazzo, A. , Lucarini, M. , Eder, P. , Silva, A. M. , Santini, A. , & Souto, E. B. (2020). Polymeric Nanoparticles: Production, Characterization, Toxicology and Ecotoxicology. Molecules, 25(16), 3731. https://doi. org/10. 3390/molecules25163731

[9] Zhao B. T. . (2022). Research progress in solid electrolyte materials for lithium metal batteries. Energy Research and Management.

[10] Yang, G. , Bai, X. , Zhang, Y. , Guo, Z. , Zhao, C. , Fan, L. , & Zhang, N. (2022). A Bridge between Ceramics Electrolyte and Interface Layer to Fast Li+ Transfer for Low Interface Impedance Solid-State Batteries. Advanced Functional Materials, 33.

[11] Zhao, P. Y. , Zhang, S. , Yang, C. , Choy, K. L. , Song, Y. , & Zhang, S. (2025). Silicon Negative Electrodes for Lithium-Ion Batteries: Challenges, Advances, and Future Prospects. ChemRxiv. https://doi. org/10. 26434/chemrxiv-2025-3tfvw

[12] Li, L. , Li, S. , & Lu, Y. (2018). Suppression of dendritic lithium growth in lithium metal-based batteries. Chemical communications, 54(50), 6648-6661.

[13] Duan, H. , You, Y. , Wang, G. , Ou, X. , Wen, J. , Huang, Q. , . . . & Lai, W. H. (2024). Lithium-ion charged polymer channels flattening lithium metal anode. Nano-Micro Letters, 16(1), 78.