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A Review of Research Progress in Solid-state Batteries for New Energy Vehicles

Runpei Cao

Qingdao 58th Middle School, Qingdao, Shandong, 266100, China

ABSTRACT
Solid-state batteries, as next-generation power battery technology, have become a focal point in the global new energy vehicle industry competition due to their advantages of high energy density, safety, and a wide operating temperature range. This paper systematically reviews global research progress in solid-state batteries from 2018 to 2023, employing a four-dimensional analytical framework encompassing materials, interfaces, manufacturing processes, and systems. Utilizing bibliometric analysis, comparative analysis, and case studies, it focuses on breakthroughs in the performance of sulfide, oxide, and polymer electrolyte materials; recent advances in interface engineering; and innovations in large-scale manufacturing processes. Research findings indicate that while significant breakthroughs have been achieved in fundamental research, solid-state batteries still face industrialization bottlenecks such as material environmental sensitivity, interfacial contact failure, and low manufacturing yield. This study proposes a multi-field coupled theoretical model integrating "interfacial chemistry-mechanical stress-electrochemical performance" and constructs a convergent development pathway combining "material genome engineering + intelligent preparation + full life cycle management," providing theoretical foundations and policy recommendations for China's solid-state battery industry development.

KEYWORDS
Solid-state batteries; New energy vehicles; Electrolytes; Interface engineering; Manufacturing processes

1 Introduction

1.1 Research Background

Amidst the global energy transition and the advancement of carbon neutrality goals, the new energy vehicle industry is experiencing rapid development opportunities.As the core component of new energy vehicles, the technological level of power batteries directly determines the vehicle's performance, safety, and cost. Commercially available liquid lithium-ion batteries currently face three major technical bottlenecks: energy density approaching theoretical limits (300–350 Wh/kg), significant thermal safety hazards, and severe performance degradation at low temperatures. According to statistics from the China Automotive Power Battery Industry Innovation Alliance, 87% of spontaneous combustion incidents involving new energy vehicles in China during 2022 were related to battery thermal runaway.

Solid-state batteries utilize non-flammable solid electrolytes, fundamentally resolving safety concerns while offering significant technical advantages: theoretical energy density exceeding 500 Wh/kg, an expanded operating temperature range of -40°C to 150°C, and an anticipated cycle life surpassing 3,000 cycles. CATL's latest semi-solid-state battery test data indicates an energy density of 360 Wh/kg, with a thermal runaway initiation temperature elevated to over 400°C and capacity retention exceeding 80% at -30°C.

The development of solid-state battery technology is receiving high-level attention at the national level. The New Energy Vehicle Industry Development Plan (2021-2035) issued by the State Council in 2023 designates solid-state batteries as a core technology for breakthroughs during the 14th Five-Year Plan period, explicitly setting mandatory targets of ⩾400 Wh/kg for cell energy density and >2000 cycles for cycle life by 2025. The "Notice on Launching Key R&D Projects for New Energy Vehicle Power Batteries," jointly issued by the Ministry of Finance and the Ministry of Industry and Information Technology, established a dedicated "Key Technology Research for All-Solid-State Batteries" initiative. Central government funding of RMB 1.2 billion supports collaborative R&D efforts among industry, academia, and research institutions.

From an international competitive perspective, major global economies have elevated solid-state battery R&D to national strategic priorities. The United States has invested US$250 million through the Battery500 program, collaborating with Tesla and QuantumScape, among others, to accelerate industrialization. Japan's "All-Solid-State Battery R&D Plan" has formed an industrial alliance including Toyota and Panasonic, aiming for the mass production of sulfide solid-state batteries by 2027. The EU's Battery 2030+ initiative commits €1.8 billion to breakthroughs in oxide solid-state battery technology. The Chinese Academy of Engineering's White Paper on China's New Energy Vehicle Industry Development (2023) states: "Solid-state battery technology has become a new competitive frontier in the global automotive industry

* **Corresponding Author:** Runpei Cao, wintercao0919@outlook.com

and represents a critical breakthrough for China's strategy to become a leading automotive power."

1.2 Research Landscape

Global solid-state battery R&D exhibits a three-pronged development framework: "electrolyte material innovation leading the way, breakthroughs in interface engineering, and manufacturing process innovation." In the sulfide electrolyte field, the Kanno team at the Tokyo Institute of Technology successfully enhanced the room-temperature ionic conductivity of $Li_{10}GeP_2S_{12}$ to 25 mS/cm through a Ge/Sn co-doping strategy [1].

Significant breakthroughs have been achieved in oxide electrolyte research. The cubic phase LLZO, discovered by the Goodenough group, demonstrated conductivity enhanced to the 10^{-3} S/cm order through Ta doping [2], opening new avenues for the development of oxide electrolytes. The Li Hong group at Tsinghua University employed grain boundary engineering to surpass a critical current density of 2 mA/cm² in LLZO films [3], clearing obstacles for high-energy-density lithium metal anode applications.

In polymer-based electrolytes, Zheng et al. at MIT incorporated metal-organic framework (MOF) materials into a polyethylene oxide (PEO) matrix, elevating the lithium ion migration number to 0.8 [4]. This innovation markedly enhanced the ionic transport properties of polymer electrolytes. Domestically, a "sandwich" structure polymer electrolyte designed by the Beijing Institute of Technology extended the cycle life of NCM811 batteries by 300% [5]. This achievement, published in Nature Materials, was selected as an ESI Highly Cited Paper.

Breakthroughs have been achieved in interface engineering. The Cui team at Stanford University employed atomic layer deposition to construct an Al_2O_3 interface layer, reducing impedance by 86% [6]. This method has been adopted by QuantumScape. Researchers at the Max Planck Institute in Germany discovered that the spontaneous Li_3N interface phase effectively suppresses sulfide decomposition [7].

In manufacturing processes, QuantumScape's oxide electrolyte thin-film deposition technology achieved ±0.1μm thickness control [8], laying the groundwork for mass production. CATL's dry electrode process elevated the cathode packing density to 4.8 g/cm³ [9], substantially boosting volumetric energy density. Regarding industrialization, Toyota announced plans to mass-produce electric vehicles equipped with sulfide solid-state batteries by 2025 [10].

Overall, solid-state battery research for new energy vehicles still faces challenges including an energy density ceiling, prominent safety concerns, and insufficient environmental adaptability.

1.3 Research Questions

Based on the analysis of the current research landscape, this paper poses the following research questions:

(1) What are the respective advantages and limitations of different solid-state electrolyte material systems (sulfide, oxide, polymer) in terms of key performance metrics? (2) What breakthroughs have been achieved in interface engineering technologies for addressing solid-solid interface contact and stability issues? (3) How do large-scale manufacturing processes influence the industrialization timeline and cost structure of solid-state batteries? (4) How can multi-field coupled theoretical models be constructed to guide solid-state battery R&D and industrialization?

1.4 Research Methodology Overview

This study employs a systematic literature review methodology, integrating bibliometricanalysis, inductive summarization, comparative analysis, and case studies to establish afour-dimensional analytical framework encompassing "materials-inter face-process-system." Through the systematic collation of high-caliber academic papers, patents, and industry reports within the global solid-state battery domain from 2018 to 2023, quantitative and qualitative analyses of key technological advancements are conducted.

2 Research Methodology

2.1 Relevant Theories

The analytical framework is grounded in systems theory and Technology Readiness Level (TRL) theory. Systems theory treats solid-state battery technology as a complex whole comprising four subsystems: material systems, interface structures, manufacturing processes, and system integration. It emphasizes the interconnections and synergistic interactions among these subsystems. TRL theory categorizes technological development into nine stages (1–9), enabling the assessment of each sub-technology's progression from laboratory research to industrial readiness.

Multiphysics coupling theory forms a crucial part of the theoretical foundation. Solid-state batteries involve complex interactions among multiple physical fields during operation, including electrochemical fields (ion/electron migration), stress fields (volume changes, interfacial stresses), and thermal fields (heat generation/dissipation). Traditional single-domain analyses struggle to elucidate failure mechanisms, necessitating the development of a multiphysics coupling theoretical model integrating "interfacial chemistry-mechanical stress-electrochemical performance."

2.2 Theoretical Enhancements

This study integrates and refines conventional theories, proposing a " multi-scale-multi-physics-multi-dimensional" collaborative analysis framework: At the multi-scale level, the analytical perspective spans from the atomic/molecular scale (electrolyte crystal structural defects) to the micrometer scale (grain boundaries, interfacial phases) and the macroscale (cell structure design), enabling a multi-tiered understanding of the relationship between performance and structure.

At the multi-physics level, the multi-field coupling theory is elevated from a purely mechanistic analysis to a systematic analytical tool. This requires consideration of electrochemical-mechanical-thermal coupling effects when evaluating any technological advancement, enabling a comprehensive assessment of its practical application potential.

At the multi-dimensional level, the integration of Technology Readiness Level assessment with economic viability (cost) and sustainability (recycling) dimensions establishes a more comprehensive evaluation framework. For instance, even a technology with a high TRL may face limited industrialization prospects if its costs significantly exceed projections or recycling proves challenging.

2.3 Research Design and Data Analysis

This study employs a systematic literature review design, drawing data from peer-reviewed academic papers in databases such as Web of Science and Scopus, granted patents in databases including USPTO, EPO, and SIPO, and authoritative industry reports from sources like BloombergNEF and IDTechEx.

The search strategy employed the keyword combination: ("all-solid-state battery" OR "solid state battery") AND ("sulfide electrolyte" OR "oxide electrolyte" OR "polymer electrolyte") AND ("interface engineering" OR "interfacial modification") AND ("manufacturing" OR "process"), with the timeframe restricted to 2018–2023.

Data analysis employed a combined quantitative and qualitative approach:

(1) Quantitative analysis: Statistical analysis of performance parameters including room-temperature ionic conductivity, interfacial impedance, critical current density, and cycle life, calculating averages, ranges, and development trends. (2) Qualitative analysis: Summarized, categorized, and comprehensively assessed technical pathways, policy orientations, and industrialization challenges. (3) Comparative analysis: Performance metrics of different technical pathways were juxtaposed for comparison, incorporating cost and environmental factors into a SWOT analysis.

3 Research Findings

3.1 Summary of Findings

Through a systematic review of the global solid-state battery sector from 2018 to 2023, this study identifies significant advancements across materials, interfaces, and processes. However, development remains uneven across technical pathways, with industrialization still facing multiple challenges.

3.2 Data Presentation

Table 1 Comparison of Key Performance Parameters for Three Types of Solid-State Electrolytes (2018–2023)

Performance Parameter	Sulfide Electrolytes	Oxide Electrolyte	Polymer Electrolyte
Room-Temperature Ionic Conductivity (S/cm)	10☒^{2} to 10☒^{1}	10☒^{6} to 10☒^{3}	10☒^{7} to 10☒^{4}
Electrochemical window (V vs. Li/Li☒)	1.7–2.1 / >5	>5 / >6	~4
Mechanical strength (GPa)	0.1–1	10-15	10☒^{3}~0.1
Stability towards lithium metal	Poor	Good	Moderate
Environmental stability	Very poor	Excellent	Excellent

Interface engineering breakthrough data:

(1) Interface impedance reduced from >1000 Ω·cm^2 to <100 Ω·cm^2 (optimal <5 Ω·cm^2) (2) Critical current density increased from 0.2 mA/cm^2 to 2.5 mA/cm^2(3) Cycle life extended from tens of cycles to >1000 cycles (80% capacity retention)

Manufacturing Process Advancements:

(1) Electrolyte film thickness reduced from 100μm to 3μm; (2) Cathode loading increased from 3 mg/cm^2 to 35 mg/cm^2; (3) Cathode packing density increased to 4.8 g/cm^3

3.3 Results Description

Research indicates that sulfide electrolytes exhibit outstanding ionic conductivity (see Figure 1), yet their environmental sensitivity and instability towards lithium metal severely constrain industrialization. Oxide electrolytes offer the most balanced comprehensive performance, but low room-temperature conductivity and high rigidity resulting in poor solid-solid contact remain key challenges. Polymer electrolytes offer excellent flexibility and low manufacturing costs, yet their application is restricted by low ionic conductivity and a narrow electrochemical window.

Significant advances have been made in interfacial engineering, where nanoscale surface modification techniques effectively reduce impedance and suppress dendrite growth. However, achieving large-area, low-cost, and uniform fabrication remains a bottleneck for industrialization. Regarding manufacturing processes, breakthroughs in dry electrode technology and thin-film preparation techniques have laid the foundation for large-scale production, though yield and cost control still require optimization.

3.4 Comparative Analysis

From an industrialization perspective, distinct maturity gaps exist across different technical pathways:

(1) Sulfide systems: Japanese firms such as Toyota and Panasonic lead the field, having established pilot production lines, though the entire supply chain requires stringent environmental control.(2) Oxide systems: Multiple enterprises in China, the US, and Europe are focusing on this area, with the large-scale preparation and cost of electrolyte films being the primary bottlenecks. (3) Polymer systems: Commercial applications exist, but high-temperature operating modes constrain vehicle energy efficiency and starting performance.

4 Discussion

4.1 Summary of Findings

This study systematically reviews recent advances in solid-state batteries across three dimensions: materials, interfaces, and processes. The findings indicate significant breakthroughs in fundamental research, yet their translation into engineering applications faces formidable challenges. Multiphysics coupling effects are pivotal to understanding the operating mechanisms and failure modes of solid-state batteries, necessitating interdisciplinary collaboration to overcome industrialization bottlenecks.

4.2 Interpretation of Findings

Advancements in solid-state battery technology have benefited from the application of nanotechnology and advanced characterization techniques, enabling researchers to gain insights into ion transport mechanisms and interfacial degradation processes at the atomic/nanoscale. The introduction of computational materials science and machine learning has accelerated material screening and optimization processes, shifting from a trial-and-error approach to predictive methodologies.

However, the performance of laboratory-scale batteries often fails to replicate when scaled up to Ah-level cells, reflecting scale effects and system integration challenges during engineering. A fundamental tension exists between the precision required for interface engineering techniques and the cost-efficiency demands of mass production, necessitating innovative solutions.

4.3 Limitations

The limitations of this study manifest in three primary aspects: firstly, reliance on publicly available literature and patents, as core technological details are typically proprietary, potentially introducing evaluation bias; secondly, inconsistent testing conditions across different research teams, limiting data comparability; thirdly, rapid technological advancement, with the latest developments potentially excluded.

4.4 Practical Applications

This research offers guidance for corporate R&D, policy formulation, and investment decisions. Enterprises may formulate R&D strategies based on the technology map; government departments may establish targeted research programs by referencing technical bottlenecks and development pathways; investors may rationally assess investment risks using maturity analysis and market forecasts.

5 Conclusion

This study employs a four-dimensional analytical framework—"materials-interface-process-system"—to systematically review global solid-state battery technology advancements from 2018 to 2023. Key conclusions are as follows:

(1) The three major solid-state battery electrolyte systems each possess distinct characteristics, yet no single material can fully meet all industrialization requirements. Future development will focus on composite and hybrid systems. (2) Interface engineering represents the most significant area of advancement, with nanoscale interface design substantially enhancing battery performance, though industrialization faces cost challenges. (3) Novel processes such as dry electrode fabrication offer viable pathways for scaled manufacturing, though yield and cost control require further optimization. (4) Multiphase coupling theory is pivotal for understanding solid-state battery mechanisms, necessitating an interdisciplinary R&D paradigm.

Looking ahead, breakthroughs in solid-state battery technology demand deep interdisciplinary integration across materials science, chemistry, mechanics, and electronics, alongside open collaboration across the industrial chain. The next 5-10 years are anticipated to be a critical window for transitioning solid-state batteries from laboratory to industrialization. China must seize this opportunity to realize its strategy of becoming a leading automotive nation.

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