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Review on Key Technical Bottlenecks and Research Progress in Industrialization of Solid-State Batteries

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Abstract: Driven by the growing demand for high-safety, high-energy-density power batteries in the new energy vehicle industry, solid-state batteries have become the core direction of next-generation energy storage technology. Replacing flammable organic electrolytes with solid-state electrolytes, they fundamentally reduce thermal runaway risks and enable lithium metal anodes for higher energy density. While semi-solid-state batteries have entered initial commercial application, all-solid-state batteries remain in the transition from laboratory research to engineering application, constrained by bottlenecks in electrolyte performance, solid-solid interfaces, preparation processes and manufacturing costs. This paper sorts out mainstream technical routes of solid-state batteries, analyzes core technical barriers to large-scale application, summarizes latest research breakthroughs worldwide, and prospects the industrialization evolution path, to provide references for relevant research and industrial practice.

Keywords: solid-state battery; industrialization; solid-state electrolyte; interfacial impedance; preparation process

1. INTRODUCTION

Under the "dual carbon" strategy, the global new energy vehicle industry maintains rapid growth, and the energy density and safety of power batteries directly determine product competitiveness. Traditional liquid lithium-ion batteries are approaching their theoretical energy density ceiling, and the flammability of organic electrolytes brings persistent thermal runaway risks, which cannot fully meet the demand for long-range, high-safety high-end electric vehicles. With advantages of electrolyte-free flammability, lithium metal anode compatibility and wide temperature adaptability, all-solid-state lithium batteries have become the strategic focus of global power battery technology competition.

Solid-state batteries evolve along the gradient path of "semi-solid—quasi-solid—all-solid". Semi-solid-state batteries have achieved mass production and vehicle installation, marking the start of industrialization. However, the commercialization of all-solid-state batteries still faces prominent challenges, with repeated delays in mass production schedules of leading enterprises, reflecting far more complex engineering implementation than expected. Although abundant achievements have been made in basic research such as electrolyte conductivity improvement and interface modification, practical obstacles including insufficient material stability, complex processes and high costs still exist in the scaling-up process. Focusing on the core issues of solid-state battery industrialization, this paper systematically sorts out technical routes, analyzes key bottlenecks and summarizes research progress, to provide theoretical support for industrial upgrading and relevant teaching and research.

2. Mainstream Technical Routes and System Characteristics

Technological Evolution Stages

According to the liquid component content in electrolytes, solid-state batteries are divided into three categories:

Semi-solid-state batteries: Retain less than 10% liquid electrolyte, highly compatible with existing liquid battery production lines with low modification cost. As the current mainstream commercial solution, they reach an energy density of 270–320 Wh/kg.

Quasi-solid-state batteries: Liquid component drops below 5%, with solid phase as the continuous electrolyte matrix. As the intermediate form to all-solid state, they are currently in pilot verification.

All-solid-state batteries: Contain no liquid electrolyte, compatible with lithium metal anodes with a theoretical energy density over 500 Wh/kg. As the ultimate technical form, they are still in the early engineering breakthrough stage.

2.2 Core All-Solid-State Electrolyte Systems

2.2.1 Sulfide Electrolytes

As the technical route closest to mass production, sulfide electrolytes feature the highest room-temperature ionic conductivity (some systems exceed liquid electrolytes) and low grain boundary resistance, suitable for densification via cold pressing. However, they have poor chemical stability, react with moisture to produce toxic gas, require strict production environment and cause high costs. Their narrow electrochemical window also leads to severe interfacial side reactions with high-nickel cathodes and lithium anodes. In recent years, doping modification has significantly improved their air stability, promoting practical application.

2.2.2 Oxide Electrolytes

Represented by garnet-type LLZO systems, oxide electrolytes have excellent thermal and electrochemical stability, are air-insensitive and have lower production requirements than sulfides. Nevertheless, they have lower room-temperature conductivity and large grain boundary impedance, requiring high-temperature sintering for dense membranes with high energy consumption and processing difficulty. Currently, they are mostly used in composite electrolytes combined with polymer matrices, which is the mainstream scheme for semi-solid-state batteries.

2.2.3 Polymer and Halide Electrolytes

PEO-based polymer electrolytes have good flexibility, easy film formability and good interface contact, but low room-temperature ionic conductivity, requiring operation above 60℃ for power battery applications. Halide electrolytes, as an emerging route, have high ionic conductivity and excellent high-voltage stability (>5 V), well matched with high-nickel cathodes. However, they have poor stability against lithium metal anodes and relatively high cost, still in the transformation stage from basic research to application.

3. Key Technical Bottlenecks in Industrialization

3.1 Intrinsic Performance and Stability of Solid Electrolytes

Current mainstream electrolyte systems can hardly meet the three industrialization requirements of high conductivity, high stability and easy processability simultaneously. Except for partial sulfide systems, most solid electrolytes have lower room-temperature conductivity than liquid electrolytes, resulting in poor rate performance and insufficient fast-charging capability.

In terms of stability: sulfide electrolytes are highly air-sensitive, requiring full-process inert gas protection with high industrial chain costs; oxides are prone to element interdiffusion with lithium metal anodes; polymers face oxidative decomposition under high voltage and lithium dendrite penetration risks. In addition, there is a trade-off between mechanical properties and dendrite suppression: rigid electrolytes tend to cause interface peeling, while flexible electrolytes cannot effectively block dendrite puncture.

3.2 Solid-Solid Interfacial Impedance and Cycle Stability

Interface issues are the core obstacle to solid-state battery industrialization. Unlike liquid electrolytes that fully infiltrate electrodes, solid-solid contact only exists at point level with small effective area, leading to much higher interfacial impedance and poor cycle stability.

On the cathode side, chemical side reactions form insulating interface products; the volume deformation of cathode materials during charge-discharge exceeds 10%, causing interface gap and peeling after repeated cycles, which breaks ion transport channels. On the anode side, drastic volume change during lithium deposition/stripping leads to poor interface contact, and dendrites growing along grain boundaries easily cause internal short circuits. Currently, most laboratory all-solid-state batteries have a cycle life of less than 1000 cycles, far below the 2000-cycle requirement for vehicle applications.

3.3 Large-Scale Preparation Processes and Equipment

Performance of laboratory coin cells degrades significantly when scaled up to large-format cells, mainly due to immature preparation processes. First, ultra-thin electrolyte membranes (<20 μm) are difficult to prepare, as it is challenging to ensure density, mechanical strength and yield in large-area production. Second, composite cathode preparation is complex, and domestic dry electrode equipment is still immature. Third, sulfide production lines require ultra-low dew point environment, with equipment investment much higher than traditional liquid battery lines, and core equipment mostly relies on imports.

3.4 Manufacturing Cost and Industrial Chain Support

The cell cost of all-solid-state batteries is 4–10 times that of mainstream lithium iron phosphate batteries, and semi-solid-state batteries are also 10%–30% more expensive than traditional ternary batteries, lacking market competitiveness. High costs mainly come from expensive raw materials, low preparation yield, insufficient scale effect and high system integration costs. In addition, the solid-state battery industry chain is not yet complete, with imperfect raw material supply, special equipment and testing standards, and insufficient upstream and downstream coordination.

4 Research Progress and Breakthrough Paths

4.1 Optimization of Electrolyte Material Systems

Multi-system integration has become the mainstream trend of electrolyte R&D. For sulfide systems, anion doping and cation substitution significantly inhibit hydrolysis and interfacial side reactions while maintaining high conductivity, and some studies have achieved stable interface contact without external pressure. For oxide systems, coated sintering technology reduces production cost by over 90%, breaking the cost bottleneck of large-area dense membrane preparation. Polymer-inorganic composite electrolytes combine the advantages of both components and are compatible with existing coating processes, with strong industrial adaptability.

4.2 Breakthroughs in Interface Regulation

Systematic??solutions??have??been??formed??from??three??dimensions????interface??modification??insitu??construction??and??structural??design??On??the??cathode??side??nanoscale??fast??ion??conductor??coating??physically??blocks??direct??contact??between??cathode??and??electrolyte??reducing??interfacial??impedance??by??more??than????July????gradient??electrolyte??design??balances??ion??transport??and??interface??stability??On??the??anode??side??artificial??SEI??films??effectively??reduce??impedance??and??suppress??dendrite??growth??Besides??integrated??electrodeelectrolyte??structures??realize??molecularscale??interface??fusion??fundamentally??eliminating??contact??impedance??of??traditional??solidsolid??interfaces

4.3 Innovation of Preparation and Mass Production Technologies

Process innovation is the key to scaling up from laboratory to mass production. New technologies such as melt infiltration and integrated tape casting-cold pressing are gradually maturing, compatible with roll-to-roll mass production. The dry electrode process is developing rapidly: it avoids solvent-induced electrolyte decomposition and produces high-density electrodes, and domestic enterprises have mastered hundred-micron dry electrode preparation technology. At the system integration level, innovations such as self-healing interfaces and viscous electrolytes enable stable cycling without external pressure, supporting lightweight and low-cost battery integration.

5. Industrialization Path and Prospect

5.1 Phased Industrialization Evolution

The industrialization of solid-state batteries follows a gradient advancement path, roughly divided into three stages:

2024–2027: Large-scale penetration of semi-solid-state batteries. They will first be popularized in medium and high-end vehicles, with an estimated market penetration of over 15% and energy density exceeding 350 Wh/kg by 2027.

2027–2030: Small-batch application of quasi-solid-state and sulfide all-solid-state batteries. They will be gradually applied in high-end models and special scenarios, with energy density reaching 400–450 Wh/kg.

After 2030: Large-scale popularization of all-solid-state batteries. When cost and life indicators meet requirements, they will comprehensively reshape the power battery industry.

5.2 Future Research Directions

Future research will focus on four directions: first, low-cost electrolyte synthesis and preparation technologies to reduce material costs by an order of magnitude; second, long-term interface stability mechanisms to develop self-healing and adaptive interface technologies; third, localization of core equipment and mass production processes to establish a standardized production system; fourth, improvement of standard and testing systems to guide standardized industrial development.

6. Conclusion

As the core next-generation power battery technology, solid-state batteries have unparalleled advantages over traditional liquid batteries in safety and energy density, and are the key support for the continuous upgrading of the new energy vehicle industry. At present, semi-solid-state batteries have achieved commercial breakthroughs, while all-solid-state batteries are at the critical transition from technical research to engineering application, restricted by four core bottlenecks: insufficient electrolyte performance, poor interface stability, immature preparation processes and high manufacturing costs.

In recent years, global breakthroughs in highly stable sulfide electrolytes, in-situ interface regulation and dry preparation processes have gradually cleared obstacles to industrialization. With continuous iteration of material systems, maturing preparation processes and improving industrial chain support, solid-state batteries will realize large-scale application along the path from semi-solid to all-solid state, and promote the new energy vehicle industry to a new stage of higher safety and longer range.

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