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Materials challenges in high-energy batteries enabling ultra-fast charging and non-flammable performance for electric vehicles

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Development of advanced battery technologies for electric vehicles (EVs) has primarily focused on achieving high energy density, non-flammability, and fast charging capability. While commercial batteries have served as the backbone for EVs, numerous material challenges still remain to achieve these desired advancements. This perspective presents an overview of state-of-the-art strategies and recent breakthroughs aimed at overcoming the limitations of next-generation EV batteries.

KEYWORDS

lithium-ion battery, material, high-energy, fast charging, non-flammability

1 Introduction

The transition to electric vehicles (EVs) is driven by the need for sustainable transportation solutions and growing concerns about their environmental impact (Tomaszewska et al., 2019). The main approach to accelerate this transition is to advance battery technologies that offer high-energy density, ultra-fast charging, and enhanced safety (Wu et al., 2019; Kim, 2022). These features are key to improving user convenience and ensuring reliable performance under practical conditions. Developing next-generation EV batteries requires a comprehensive understanding of material selection, electrode design, optimization, and in-depth characterization (Wu et al., 2020a). However, significant material-related challenges remain in simultaneously achieving these performance goals.

Silicon (Si) and lithium (Li) metal are considered ideal anode candidates due to their high theoretical capacities—3,579 and 3,860 mAh g⁻¹, respectively—and, in the case of Li, the lowest redox potential (−3.04 V vs. standard hydrogen electrode) (Obrovac and Krause, 2006; Xu et al., 2014). Yet, both Si and Li metal anodes suffer from severe volume changes during cycling, which compromise interfacial stability and cycle performance. To overcome these intrinsic limitations, various strategies have been developed, such as using electrolyte additives, applying protective surface layers to stabilize the SEI, and designing 3D architectures to suppress volume expansion (Zhao et al., 2024; Yuan et al., 2022). On the cathode side, nickel (Ni)-rich oxides offer high energy density but exhibit structural

instability during high-voltage cycling (Li et al., 2015). To achieve higher specific capacities and energy, Li excess cathode materials, such as disordered rocksalt, lithiated spinel, Li-rich, Mn-rich, and sulfur cathodes have gained significant attention (Fergus, 2010; Chen et al., 2024). In particular, Li-rich oxide materials, which are advantageous under high-voltage operations, are being explored to support high-energy density Li-ion batteries (LIBs) and compensate for Li loss (Johnson et al., 2008).

Furthermore, ultra-fast charging technologies capable of achieving a 90% state of charge within 10 min are crucial to approach the convenience of conventional fueling. Achieving this goal requires innovations in electrode architecture, ion transport kinetics, and thermal management to safely and efficiently accommodate the high current demands (Li et al., 2021). From a safety viewpoint, the replacement of flammable organic electrolytes with solid-state alternatives is inevitable. These non-flammable solid-state electrolytes (SEs) significantly enhance thermal stability and reduce explosion risk, marking a critical step toward safe and high-performance EV batteries (Jonderian and McCalla, 2021). This perspective outlines key materials challenges and highlights emerging strategies that will enable the widespread adoption of EVs in terms of LIBs, helping pave the way toward next-generation energy storage.

2 High-energy density batteries

Achieving high-energy density is a fundamental requirement for next-generation LIBs, especially to extend EV driving range and reduce battery size (Khan et al., 2023). From a materials perspective, selecting high-capacity anode and cathode materials and ensuring harmony between the two is necessary.

Si is highly desirable as a high-capacity anode, offering a theoretical capacity nearly ten times that of commercially used graphite (372 mAh g⁻¹) (Shu et al., 1993). Notably, Si is abundant, cost-effective, and environmentally friendly, making it attractive for practical applications. However, its utilization is hindered by intrinsic properties. During lithiation, Si particle undergoes substantial volume expansion (~300%), causing particle pulverization, continuous SEI rupture/reformation, and irreversible Li loss, all contributing to rapid capacity fading (McBrayer et al., 2023). Recent studies have focused on nano-sized Si particles embedded within a porous carbon framework, which effectively buffers volume expansion and suppresses unstable SEI formation (Cho et al., 2025). This composite maintained structural integrity over extended cycling and improved electrochemical reversibility under high currents. This hybrid architecture verified a promising strategy for next-generation Si anode, where mechanical accommodation, electron/ion transport pathways, and interface stability are simultaneously engineered to enable practical high-energy LIBs (Lee et al., 2019).

From another perspective, Li metal is also an ideal anode material for high-energy batteries. However, its practical application is limited by high reactivity and interfacial instability (Wang et al., 2020). During repeated Li plating and stripping, severe volume changes in the metallic Li electrode disrupt and reform the SEI, promoting dendritic Li growth that penetrates the separator and results in internal short circuits (Bassett et al., 2023). In addition to

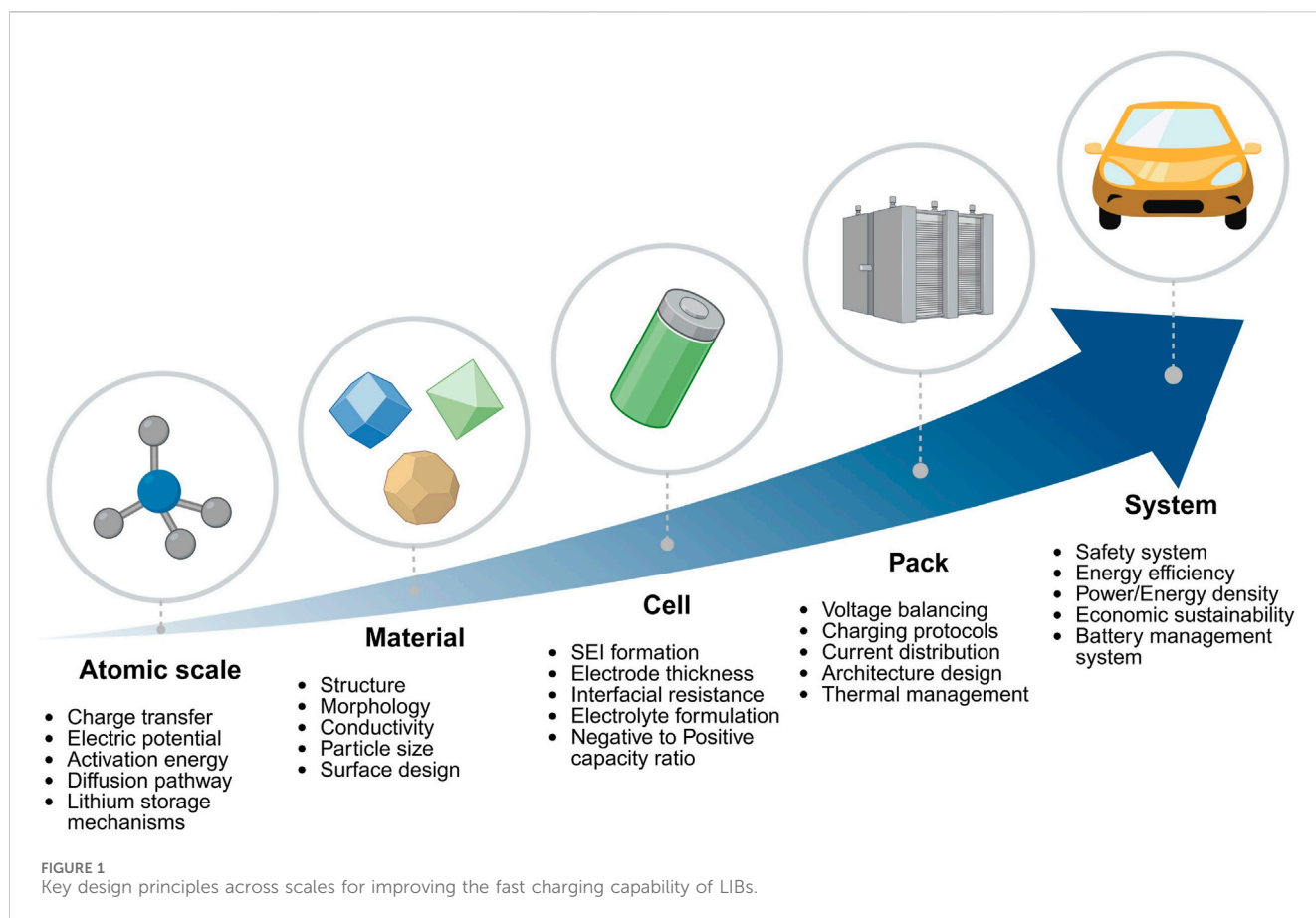
safety risks, Li dendrites form electrically isolated 'dead Li', accelerating performance degradation. One of the most effective strategies to suppress dendrite formation is the formation of a robust, ionically conductive artificial SEI through electrolyte additives, which promotes uniform Li-ion transport (Cheng et al., 2016). For instance, incorporating LiNO₃ into ether-based dual-salt electrolytes has been reported to induce the formation of a homogeneous SEI with high ionic conductivity (~10⁻⁴ S cm⁻¹) and improved ion flux uniformity (Vu et al., 2021). Nonetheless, the poor solubility of LiNO₃ in carbonate-based electrolytes remains a key limitation. To overcome this, alternative compounds, such as Li₂S, Li₃P, and LiAl₅O₈, have been explored (Park et al., 2023a).

Cathode materials are key to determining overall battery performance. Among them, LiNi_xCo_yMn_zO₂ layered oxides with Ni content >80% (Ni-rich NCM) cathode materials have emerged as dominant cathode materials in commercial EV batteries, offering higher energy density (>200 mAh g⁻¹) compared to lithium cobalt oxide (LiCoO₂) (140 mAh g⁻¹) (Sun et al., 2009; Chen and Dahn, 2003). Increasing the nickel content in NCM materials enhances reversible capacity as Ni undergoes a redox transition from +2 to +4, allowing the transfer of more electrons than other transition metals. However, the high-voltage operation of Ni-rich NCM materials induces abrupt changes in the *c*-axis lattice parameter, generating microcrack formation along secondary particles (Hong et al., 2024). These microcracks further enlarge the interface between cathode material and electrolytes, which increases internal resistance and reduces the rate performance. Recent studies show that surface coating, doping, and electrolyte optimization can mitigate these issues and enhance both rate capability and cycling stability (Sofian et al., 2024). In this context, Li-rich layered oxide [LLO, Li_{1+x}TM_{1-x}O₂ (TM = Mn, Ni, Co., etc., 0 < *x* ≤ 0.33)] has gained significant attention as next-generation cathode material due to their high average voltage (>3.6 V) (He et al., 2023). Moreover, LLO exhibits higher specific capacity (>300 mAh g⁻¹) benefiting from additional capacity attributions through anionic redox activity at high potential (>4.5 V). While LLO achieves high capacities through anionic redox activity, this mechanism induces structural degradation, voltage fading, and oxygen release during cycling, which can compromise both rate capability and safety (Jang et al., 2024). Managing the atomic composition in LLO has been proposed as an effective strategy to simultaneously activate both cationic and anionic redox reactions, which helps suppress voltage decay and enhance rate performance (Liu et al., 2025).

From a broader perspective, realizing high-energy LIBs requires the successful integration of advanced anode and cathode materials with stable interfaces and engineered structures that can accommodate mechanical and chemical instabilities during cycling.

3 Ultra-fast charging batteries

Under ultra-fast charging conditions, conventionally available graphite anodes meet significant limitations in uniformly accommodating Li-ions (Liu et al., 2023). Fast charging of batteries involves the rapid extraction of Li-ions from the cathode and their subsequent intercalation into the anode. During this process, the intercalation of Li-ions into graphite requires Li-ions desolvation from the solvent shell, which is



considered a rate-determining step (Weiss et al., 2021; Zhong et al., 2023). Faster intercalation at edge planes compared to basal planes causes non-uniform ion distribution and a sharp increase in overpotential. As polarization rises, the local potential drops below the Li/Li^+ redox potential, triggering Li plating and dendritic growth. These dendrites react with the electrolyte to form unstable SEI layers, increase interfacial resistance, and risk internal short circuits (Liu et al., 2024). As shown in Figure 1, improving fast charging capability in LIBs requires optimization across multiple scales. Among these, material-level innovations are particularly critical for enhancing ionic transport, structural stability, and interfacial properties.

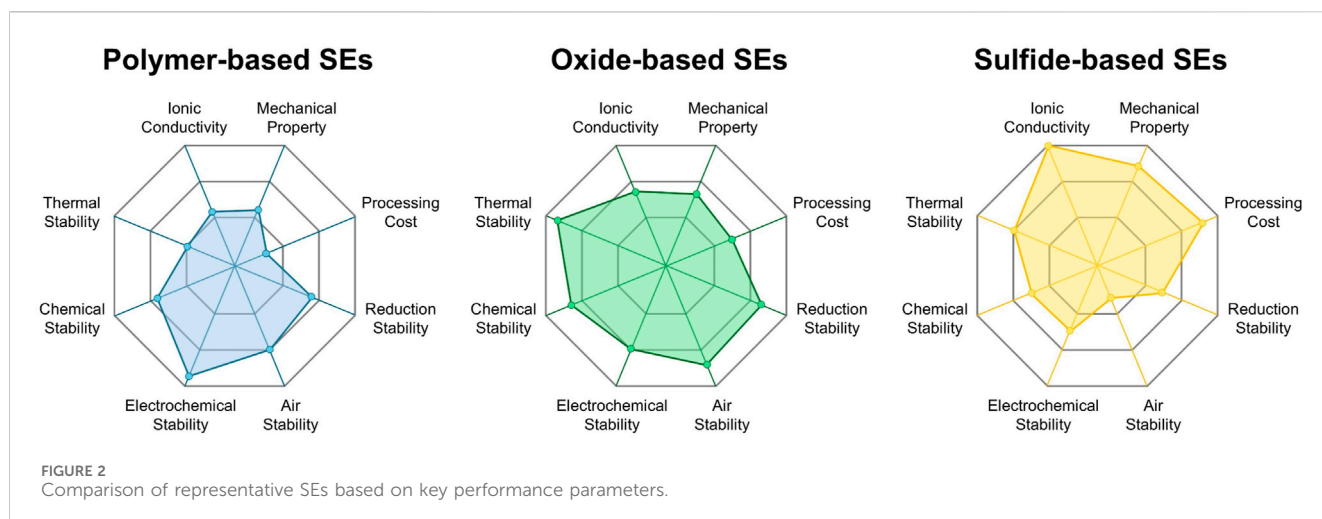
Overcoming the limitations of graphite under ultra-fast charging conditions requires a comprehensive understanding of interfacial dynamics to secure both safety and reliability in LIBs. Recent research has been directed toward interfacial engineering to prevent Li plating and improve charge transfer without sacrificing energy density. Surface coatings, particularly those based on transition metal-based compounds, have shown effectiveness in enhancing Li-ion transport, stabilizing interface, and reducing undesirable side reactions. The desired effects can be achieved with minimal coating thickness and content, preserving overall energy density of LIBs. For example, TiO_2 coatings improve both thermal stability and conductivity (Rhee et al., 2020), while Al_2O_3 coatings enhance electrolyte wettability, thereby promoting faster Li-ion transport throughout the electrode. (Kim et al., 2019). MoO_x - MoP_x /graphite composites reduce interfacial resistance

and facilitate rapid Li intercalation, achieving 80% capacity in under 10 min with stable cycling (Lee et al., 2021). Transition metals, such as Co_2P and MoS_2 , also improve interfacial stability by reducing overpotentials and forming a robust SEI (Jeong et al., 2024; Suh et al., 2025). Additionally, zeolitic imidazolate framework (ZIF)-8-derived porous carbon nanoparticles create a three-dimensional interface that enhances ion access and reduces overpotential, improving performance during fast charging (Han et al., 2024).

Continued efforts in surface chemistry engineering, SEI composition optimization, and electrode microstructure design are necessary to realize safe and reliable fast charging LIBs. The ultra-fast charging technologies must proceed in parallel with achieving high energy density, highlighting the need for advanced interfacial strategies tailored to high-capacity anodes, such as Si and Li metal.

4 Non-flammable batteries

Leakage and irreversible decomposition of liquid electrolytes during battery cycling present serious safety risks, including the potential for explosion. While additives can reduce the flammability of liquid electrolytes to some extent, they still pose safety concerns under extreme conditions (Wang et al., 2019). As a result, the adoption of solid-state electrolytes has become crucial for ensuring thermal and electrochemical safety in LIBs (Zhao et al.,



2020). They possess non-flammability, high-temperature resistance, and non-volatilization to eliminate hidden safety risks (Lv et al., 2019). For practical application in batteries, SEs must possess several key criteria: (i) high ionic conductivity, (ii) strong moisture resistance, and (iii) low interfacial impedance (Park et al., 2023b). Among these, achieving high ionic conductivity is the most critical because the primary role of SEs is to facilitate Li-ion transport between the anode and cathode.

SEs are well known to be categorized into three types, mainly including polymers, oxides, and sulfides, each offering distinct advantages for specific applications (Figure 2). Polymer-based SEs are cost-effective, as they share similar properties and manufacturing processes with conventional liquid electrolytes (Du et al., 2024). Notably, among the three SEs introduced, polymer-based SEs demonstrate the broadest electrochemical stability window, indicating their enhanced electrochemical stability. Nevertheless, a persistent trade-off exists between mechanical robustness and Li-ion conductivity (Lu et al., 2023). One promising approach to overcome this is the incorporation of active fillers. For example, black phosphorus generates an *in-situ* Li-ion conducting interfacial layer, which promotes interfacial stability and ion transport (Wu et al., 2020b). Oxide-based SEs are another prominent category, offering high chemical stability due to their resistance to reaction with Li metal at the anode and transition metal oxide cathodes (Ohta et al., 2012). However, their brittleness results in poor interfacial contact, requiring further engineering solutions (Wolfenstine et al., 2018). This issue can be managed through thickness optimization of the SE layer (Balaish et al., 2021). Importantly, sulfide-based SEs, specifically $\text{Li}_6\text{PS}_5\text{X}$ ($\text{X} = \text{Cl}, \text{Br}, \text{I}$), have garnered significant attention due to their high ionic conductivity ($1.3 \times 10^{-3} \text{ S cm}^{-1}$), which is comparable to that of liquid electrolytes (Walther et al., 2020). Despite this promising attribute, they face critical challenges including the formation of byproducts caused by reactions with SEs and cathode materials and poor moisture resistance, thereby limiting their practical application. To address this issue, moisture-absorbing additives have been proposed. For example, ZIF-8 effectively suppresses H_2S gas generation by adsorbing residual moisture (Jung et al., 2023).

The development and optimization of SEs with enhanced ionic conductivity, improved interfacial stability, and greater mechanical robustness represents crucial advancements toward enabling safer, high-performance ASSBs. Advanced synchrotron-based analysis and data-driven modeling approaches are expected to play a critical role in probing interfacial phenomena, guiding material optimization, and accelerating the development of next-generation energy storage systems.

5 Perspective

As previously discussed, advanced battery systems for EVs must feature several key characteristics: high-energy density, fast charging capability, and non-flammability. The introduction of high-capacity anode and cathode materials offers a promising route to enhance energy density, but their successful implementation requires overcoming challenges. Simultaneously, achieving reliable ultra-fast charging requires not only fast ion diffusion in electrode materials but also the design of low-resistance and stable interfaces that can support rapid Li-ion transport without promoting Li dendrite formation. On the electrolyte side, solid-state systems offer a compelling pathway to non-flammable battery architectures. High ionic conductivity must be achieved alongside electrochemical, mechanical, and moisture stability to ensure overall performance, which calls for advanced composite design and interfacial engineering.

Looking ahead, breakthroughs will not arise from single-component optimization alone, but from the co-engineered integration of functional electrode materials across all components. Success will depend on the development of scalable, compatible, and robust material systems that combine fast ion transport, interfacial stability, and mechanical resilience. Ultimately, the future of LIBs lies in the rational design of materials at multiple scales, from the atomic-level tuning of surfaces and interfaces to the system-level assembly of high-performance, safe, and manufacturable energy storage devices.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

HL: Writing – review and editing, Conceptualization, Writing – original draft, Visualization. JS: Writing – original draft, Software, Visualization, Conceptualization. RC: Conceptualization, Data curation, Formal Analysis, Writing – original draft. JM: Supervision, Writing – review and editing. JK: Funding acquisition, Supervision, Writing – original draft, Writing – review and editing, Visualization, Project administration, Conceptualization.

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