Current Status and Challenges of High-Energy and Fast-Charging Lithium-Ion Batteries for Electric Vehicles

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Abstract—**Commercial Lithium-ion Batteries (LIBs) face issues like low energy density, limited capacity, and reduced power output due to lithium plating, mechanical effects, and heat release during high-rate charging, which fail to meet the growing demands of the energy storage market. Addressing these problems is imperative through developing fast-charging LIBs with higher energy density, improved safety, lower cost, and longer life cycles. This article reviews the current developments and research progress of high-energy and fast-charging LIBs. It provides a comprehensive overview of the factors affecting the energy density and charging speed of LIBs at the levels of cathode and anode materials and electrolytes. Additionally, the paper discusses the selection and optimization of cathode and anode materials and electrolyte types. Finally, this paper shares the views on potential issues and challenges in the development of next-generation LIBs, offering data support and theoretical guidance for designing high-energy and fast-charging LIBs.**

Keywords—**Lithium-ion batteries, high-energy, fast-charging, anode, electrolyte, cathode**

I. INTRODUCTION

Commercial Lithium-ion Batteries (LIBs), first introduced by Sony Corporation in 1991, have become crucial energy storage devices with a significant impact on our daily lives [1]. Particularly, LIBs currently dominate the market in powering portable electronics and Electric Vehicles (EVs), and the energy density of LIBs at the cell level has reached 260 Wh/kg and 800 Wh/L after rapid growth over the past 32 years[2].

EVs have emerged as a compelling solution for mitigating greenhouse gas (CO_2) emissions and combating climate change. The batteries that propel these vehicles are at the core of this transformative shift. In recent years, the demand for EVs has experienced tremendous growth. Nevertheless, to expedite the widespread adoption of EVs and optimize their overall performance, it is imperative to tackle the challenges and opportunities associated with high-energy and fast-charging batteries.

The expanding EV market requires advanced batteries, emphasizing high energy density and fast charging. Among available rechargeable battery technologies, LIBs present the highest energy content, with a specific energy of approximately 250–300 Wh/kg and an energy density of around 600–700 Wh/L, equivalent to about 1/6 and 1/2 of the practical values of gasoline, respectively [3]. Commercial LIBs, using intercalation-type cathodes and graphite anodes, are approaching their intrinsic capacity limits, especially regarding their specific capacities [4, 5]. For instance, materials such as $LiFePO_4$ (LFP) and Co- and Ni-based oxides, including notably lithium Nickel Cobalt Manganese oxides (NCM), often used as commercial cathodes, encounter limitations due to their inherent maximum capacity, approximately 250 mA h g^{-1} [6]. In contrast, commercial graphite-based anodes offer a comparatively modest gravimetric capacity, around 300 mA h g^{-1} [7]. To overcome the limitations of intercalation chemistry in LIBs, innovative approaches in battery chemistry and advancements in chemical engineering for enhancing energy storage processes are urgently needed [8].

The market growth of EVs is hindered by their lengthy charging times and shorter driving ranges compared to traditional engine vehicles. The US Department of Energy aims for Extreme Fast Charging (XFC), aiming to charge up to 60% in just 15 minutes [9]. Also, various EV brands have made significant achievements in fast-charging technologies. The Model Y, produced by Tesla, can run 250 km using a supercharging station, with a charging time of only 15 minutes [10]. Regrettably, during the fast-charging process, side reactions occur within the LIBs, such as lithium plating, mechanical effects, and heat generation, which can significantly accelerate degradation, reducing battery capacity and power capability [11]. In EVs, the durability of graphite anodes and cathodes in commercial LIBs can be readily affected by XFC operations [12]. High overpotential leads to a more negative operational potential, attributed to sluggish Li^+ transport kinetics. This condition triggers lithium plating on the anode surface, creating dead lithium or dendrites. Meanwhile, the heat generation during charging will accelerate the side reaction rate and eventually result in safety problems without prompt and homogeneous dissipation. Furthermore, Li^+ transport at the interface and through the electrolyte bulk is a primary factor limiting fast charging capabilities [13].

To support the growth of the EV market, future LIBs need to be smaller, have higher energy densities, and be safer and more cost-effective. To achieve these objectives, the primary research focus has been on developing high-voltage cathodes, advancing materials with improved battery capacity, and innovating electrolytes to enhance energy densities in upcoming LIBs. It is noteworthy that existing commercial LIBs face challenges such as high costs, insufficient energy density, environmental issues, and potential safety hazards. The worldwide scientific community is progressively committed to creating next-generation LIBs characterized by increased energy densities, enhanced safety features, lower costs, and longer cycle life spans. Many energy storage materials and battery science researchers are focusing on improving crucial components of these next-generation high-energy LIBs. These components include electrode materials, electrolytes, current collectors, and innovative battery architecture design.

This comprehensive review outlines current research directions and offers essential insights into the design of materials and architectures for the next-generation LIBs, meeting the needs of a society deeply reliant on electric power. In addition, the review includes a thorough analysis of existing trends and a discussion of the fundamental operational principles and associated challenges.

II. REVIEW OF CATHODE AND ANODE MATERIALS FOR LIBS

Table 1. Summary of selected cathode and anode materials [6]

Active materials	Specific capacity mA h g^{-1}/m A h cm^{-3}	Potential (V *vs.* Li$^+$/Li)	Advantages	Disadvantages
LiFePO$_4$	170/612	3.4	Low cost, stable long cycle, commercialization	Low energy density, low specific capacity, low electronic conductivity
LiCoO$_2$	140/714	3.8	Long cycle, mature technology, high energy density, high voltage	High cost, limited capacity, significant toxicity, poor thermal stability, and irreversible phase change
High-voltage LiCoO$_2$	185/944	3.95		
LiNi$_{0.8}$Co$_{0.1}$Mn$_{0.1}$O$_2$	200/930	3.8		
LiNi$_{0.8}$Co$_{0.15}$Al$_{0.05}$O$_2$	220/979	3.6		
CuF$_2$	528/2002	3.55	High energy density, low cost, high specific capacity	Substantial voltage hysteresis, weak cycling stability, low reversibility, inadequate rate performance, material dissolution, and significant volume change
FeF$_3$	712/2196	2.74		
CoF$_2$	553/2038	2.8	High energy density, high specific capacity	
NiF$_2$	554/2040	2.96		
CuCl$_2$	399/1115	3.17	High specific capacity, low cost	Extremely soluble in liquid
S	1675/1937	2.28	Abundant, low toxicity, inexpensive, high energy density, specific capacity	Dissolution and shuttle, low electronic conductivity, low working potential, large volume change
Li$_2$S	1166/1937	2.28		
O$_2$	1675/2698	2.96	High electronic conductivity, high specific capacity	Significantly limited reaction kinetics
Li$_2$Se	578/1659	2.07		Expensive and highly toxic, dissolution and shuttle, low working potential

Understanding the fundamental science and engineering principles behind high-energy and fast-charging LIBs is essential for addressing the challenges and harnessing their opportunities. Typical cathode and anode candidates are selected and summarised in Table 1, along with their benefits and shortcomings. More details of several battery-active materials are discussed in the following sections. Overall, these batteries rely on cutting-edge materials, including advanced cathodes, anodes, and electrolytes. For instance, the development of high-capacity cathode materials such as Nickel-Cobalt-Manganese (NCM) and Nickel-Cobalt-Aluminum (NCA) has significantly improved the energy density of LIBs. Similarly, silicon anodes, solid-state electrolytes, and innovative electrode designs are paving the way for faster charging and higher energy storage.

A. Recent Advances Concerning Cathode Materials for LIBs

1) High-energy cathode materials

With the development of the lithium-ion battery industry, intercalation-type cathode materials have been widely used. These include high-voltage and commercial cathodes and the crystal structures of LiMO$_2$ (M = Ni, Co, or Mn) and its Mn- and Li-rich derivatives xLi$_2$MnO$_2$–(1−x)LiMO$_2$ (M = Ni, Co, or Mn). Commercial cathodes, like lithium iron phosphate (LiFePO$_4$, LFP), lithium manganese oxide (LiMnO$_2$, LMO), and lithium cobalt oxide (LiCoO$_2$, LCO), present low specific gravimetric and volumetric capacities (below 180 mA h g^{-1} and 750 mA h cm^{-3}) and low working potentials (below 3.8 V *vs.* Li$^+$/Li)[14]. To enhance cell energy density using current battery assembly technologies, numerous efforts have been invested by both academia and industry to explore and optimize new cathode materials. These materials aim to provide higher capacities (*e.g.*, > 200 mA h g^{-1}) and/or higher average working potentials (*e.g.*, > 3.8 V *vs.* Li$^+$/Li). In prior studies, nickel-rich, manganese-rich, lithium-rich layered oxides have been recognized as notably promising for near-term solutions [6]. The Ni-rich layered oxides family (LiNi$_{1−x}$M$_x$O$_2$, M = Co, Mn, and Al) includes LiNi$_{0.8}$Co$_{0.1}$Mn$_{0.1}$O$_2$ (NCM811, approximately 200 mA h g^{-1} and 932 mA h cm^{-3}) and LiNi$_{0.8}$Co$_{0.15}$Al$_{0.05}$O$_2$ (NCA, approximately 220 mA h g^{-1} and 980 mA h cm^{-3}). These oxides offer higher specific capacities, both gravimetric and volumetric, compared to other intercalation-type cathode materials and have found partial use in commercial product manufacturing. LiNi$_{0.6}$Co$_{0.2}$Mn$_{0.2}$O$_2$ (NCM622) and LiNi$_{1/3}$Co$_{1/3}$Mn$_{1/3}$O$_2$ (NCM333) are noteworthy, with specific capacities of roughly 170 mA h g^{-1} and 150 mA h g^{-1}, respectively. When comparing cost-effectiveness, Li-rich layered oxides, represented by formulas like Li$_{1+x}$M$_{1-x}$O$_2$ or xLi$_2$MnO$_3$–(1−x) LiMO$_2$ (where M can be Mn, Ni, Co, *etc.*), have the advantage. They can deliver capacities between 250–300 mA h g^{-1}, outperforming Ni-rich layered oxides in this aspect. The compound LiNi$_{0.5}$Mn$_{1.5}$O$_4$ (LNMO) stands out with its high working potential of 4.7 V (*vs.* Li$^+$/Li) and specific capacities of 147 mA h g^{-1} and 626 mA h cm^{-3}. Furthermore, high-voltage cycling LCO cathodes have been observed to exhibit enhanced specific capacity and working potential [15]. While polyanionic compounds, particularly phosphates, and sulfates, offer high working potentials between 4.0 V to 5.3 V (*vs.* Li$^+$/Li), despite being limited to a specific capacity of around 170 mA h g^{-1}, and Li$_2$NiPO$_4$F and LiNiSO$_4$F being highlighted as primary examples, cathode materials such as Li$_2$NiPO$_4$F (LNPF), LiCoPO$_4$ (LCP), LiMnPO$_4$ (LMP), and LiNiSO$_4$F (LNSF) demonstrate

low capacity utilization and inferior cycling performance, which limits their use in advanced high-voltage Li and LIBs.

2) Fasting-charging cathode materials

Several strategies can enhance lithium ions' conductivity and boost the battery's rate capability. These include modifying the electrode surface and controlling interface morphology, which can facilitate interface desolvation and ion migration through Solid Electrolyte Interphase (SEI). Additionally, developing composite materials and applying electrolyte additives are valuable approaches. Optimizing the electrode's macro dimension further contributes to improving ionic diffusion in electrode material. Fig. 1 provides a comprehensive summary of strategies for increasing rate capability, viewed from the perspectives of both electrodes and electrolytes [9].
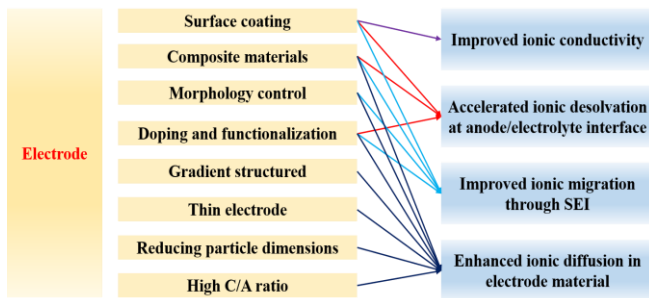

Fig. 1. General strategies for rate capability enhancement at the material level [9].

Improvement strategies for electrodes encompass a variety of approaches: surface coating, composite materials, morphology control, doping and functionalization, gradient structure, and macro-level design. Consequently, evaluating the critical size of electrode particles becomes essential to strike a balance between energy density and rate capability. Likewise, choosing the optimal areal capacity ratio of Cathode-to-Anode (C/A) is vital to inhibit lithium deposition and prevent cathode overcharging. Electrodes with high porosity or low tortuosity and electrolytes with excellent ionic conductivity are more conducive to fast charging. High-rate charging often speeds up the degradation of LIBs due to uneven current density and temperature distribution on a large scale, along with limited Li^+ diffusion kinetics on a micro-scale. The battery's rate capability is tied to the movement and diffusion of ions in the electrodes and electrolytes, as well as at their interfaces. Moreover, the main hurdle of XFC moves from being reaction-limited to transport-limited in very low temperatures. Notably, electrode materials impose more significant limitations on rate capability than electrolytes at a moderate temperature [16].

Mao *et al* [17] utilized symmetric and half cells of NMC811/graphite to examine the rate capability of the cathode and anode separately. Their findings illustrated a notable capacity fade in the graphite anode at high C-rates. While cathode degradation does expedite battery aging, it was not identified as the pivotal challenge of fast charging [18]. Furthermore, increasing the separator's porosity or reducing its thickness only slightly enhances rate capability [19].

B. Choice of Electrolyte

The electrolyte plays a crucial role in battery systems by forming ion-conductive pathways and creating a closed loop with external electron pathways. Its bulk ionic conductivity, along with the connectivity of the ion-conductive channels and electron pathways within the electrodes, greatly affects the major internal resistance of a battery. Thus, enhancing the bulk ionic conductivity of the electrolyte is vital. Similarly, enhancing the contact area and arrangement between the electrolyte and electrodes is essential, a principle that holds for both liquid and solid electrolytes. The improvement in rate performance is mainly attributed to the higher electrolyte conductivity and enhanced interface dynamics. Moreover, maintaining the stability of electrolytes in relation to the electrodes is crucial for their practical use in an operational battery.

1) Electrolyte design for energy density LIBs

The solvents and lithium salts in liquid organic electrolytes must possess adequate solubility and stability. When the battery undergoes charging and discharging cycles, issues like decreased solubility, precipitation, and crystallization may occur with the solvents and lithium salts, leading to reduced battery capacity, interface instability, and electrolyte loss. The solubility and interface stability of the electrolyte are crucial factors determining the energy density and lifespan of the battery. Additionally, the solvents in liquid organic electrolytes have a certain level of volatility, especially under high-temperature conditions. This volatility can cause a decline in battery capacity and electrolyte concentration and even pose safety risks. Due to imperfect battery sealing, solvents in the electrolyte might escape and be lost during cycles, further diminishing the energy density and lifespan of the battery.

There are two commonly used types of liquid electrolytes: carbonate electrolytes for LIBs and ether electrolytes for Li–S and Li–O$_2$ batteries. For LIBs, where a 4 V or 5 V cathode is used, the electrolyte needs to withstand high voltage. Therefore, a carbonate electrolyte is preferred over an ether electrolyte because its electrochemical stability window exceeds 4.3 V, which is higher than the less than 3.5 V offered by ether electrolytes. In contrast, for Li–S and Li–O$_2$ batteries, where the voltage is usually below 3.5 V, ether electrolytes are used due to their higher chemical stability. This is especially important since polysulfides and oxygen radicals can react with carbonate solvents, causing irreversible damage. In summary, when choosing an electrolyte, the specific characteristics of each type should be carefully considered.

In recent years, researchers have extensively studied hybrid electrolytes to explore their potential applications and performance advantages in lithium-ion batteries [20]. One common form of hybrid electrolytes involves mixing different types of solvents. By combining carbonate solvents with ether solvents, the physical and chemical properties of the electrolyte can be adjusted, aiding in enhancing the energy density of the battery. Furthermore, hybrid electrolytes can also be created by mixing different types of electrolytes. Mixing various lithium salts adjusts the ion concentration and ion transport properties of the electrolyte, thereby affecting the energy density and cycle performance of the battery. Yang et al. developed an electrolyte containing Glyme-based Electrolytes (GlyEls), which, when applied to

silicon anode batteries, forms a resilient SEI layer on the silicon film surface [21]. This outer GlyEl-SEI layer is capable of withstanding stress changes, while the inner layer shows a reduced content of carbonates and silicides but an increased presence of LiF, sulfates, and SiO_xF_y. This beneficial layered structure of SEI helps improve the battery's cycling performance and reduces internal resistance and polarization. Zheng *et al.* created a high-safety, non-flammable electrolyte by dissolving 0.93 mol/L lithium bis (fluorosulfonyl) imide (LiFSI) in a novel fluorinated cyclic phosphate solvent/2,2,2-trifluoroethyl carbonate/1,1,2,2-tetrafluoroethyl 2,2,3,3-tetrafluoropropyl ether (HFE). The cyclic phosphate itself is non-flammable and assists in forming a highly elastic interphase. HFE contributes to the chemical association of Li^+ with FSI^-, creating an additional derived inorganic interface, and enhancing the electrolyte system's oxidative stability. This electrolyte shows good compatibility with NCM622 high-nickel cathodes and Si anodes, resulting in a full cell with high specific energy (590 Wh/kg) and coulombic efficiency (99.9%) [22].

2) Electrolyte design for the fast-charging LIBs

The properties of liquid electrolytes are crucial for fast charging. Typically, electrolytes used in LIBs consist of a mix of organic solvents and lithium salts, which influence the movement of ions within the electrolyte and at the interface between the electrode and electrolyte. While the ionic conductivity of the electrolyte does not majorly limit the diffusion of lithium ions, the characteristics of the SEI layer, which are determined by the electrolyte's composition, have a significant impact on the charging rate. Additionally, side reactions caused by fast charging can reduce the stability of the electrolyte. In more severe cases, internal heating or the growth of lithium dendrites can worsen the electrolyte's conductivity and trigger exothermic reactions. Therefore, developing electrolytes that support fast charging while maintaining high safety is essential.

High-Concentration Electrolytes (HCE), typically above 3 M, enhance lithium-ion batteries by adjusting the solvation structure of Li^+ [23]. Acetonitrile (AN) used in these batteries eliminates the voltage limitations of traditional carbonate-based electrolytes (≈ 4.2 V) and, with its superior ion transmission properties, could enable fast-charging lithium-ion batteries for EVs. Yamada *et al.* [24] discovered that highly concentrated AN (> 4 M) overcomes its low reduction stability, enabling reversible graphite anode reactions. High-concentration electrolytes reduce free AN molecules, leading to the primary reduction of bis (trifluoromethane)-sulfonimide $TFSI^-$ anions during the first lithium insertion. This forms a TFSI-derived interface film on the graphite anode, inhibiting further decomposition of the electrolyte. This SEI formed in the super-concentrated solution is key to enhanced reduction stability, facilitating reversible lithium insertion into graphite, which is beneficial for fast-charging lithium-ion batteries. However, HCE has disadvantages like high cost and viscosity. Recent research in lithium-ion battery electrolytes focuses on additives, like Han *et al.*'s proposal of an aminosilane-based additive, trimethylsilyl isothiocyanate (TMSNCS), which has a high electron-donating capability to neutralize Hydrofluoric acid (HF) and phosphorus pentafluoride (PF_5). TMSNCS effectively deactivates reactive substances like HF and forms stable interface layers on both electrodes [25]. A battery with 0.1% TMSNCS in NCM622||graphite cell offers a high discharge capacity of 144 mA ħ g^{-1} after 300 cycles at 2C charge and 1C discharge rates, maintaining 91.8% capacity.

C. Recent Advances Concerning Anode Materials for LIBs

At the moment, the anode materials commonly used in commercial LIBs include carbon-based options like graphite, carbon nanotubes, and graphene, as well as Lithium Titanate Oxide (LTO). Graphite stands out as a preferred choice for anode material due to its affordability, safety, and high reversibility. Nevertheless, numerous studies indicate that the formation of the SEI layer can deplete electrolytes and lithium, posing challenges to maintaining a stable interface structure. Although the thickening of the SEI layer is not the primary concern in rapid charging, it becomes problematic when it leads to the blockage of electrode pores, diminishing the battery's efficiency. It's crucial to highlight that the potential of the graphite anode closely aligns with the potential at which lithium may deposit or dissolve. In specific situations, such as rapid charging or exposure to low temperatures, the potential might fall below 0 V relative to Li/Li^+. This scenario can cause lithium ions to form metallic lithium at the interface between the anode and the electrolyte, instead of integrating into the particle structure. This phenomenon, known as lithium plating, can negatively impact the battery's lifespan and safety. Besides accelerating the battery's capacity loss, lithium plating also introduces potential safety hazards.
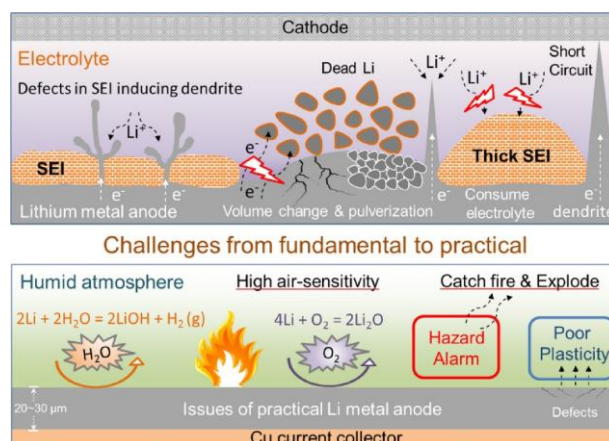

Fig. 2. The remaining challenges of Li metal anodes [26].

In addition to common graphite and LTO anodes, researchers are developing a variety of high-capacity anode materials to meet the growing demands of rechargeable batteries with better energy storage. These include materials like transition metal sulfides, oxides, and fluorides, which can store more energy than traditional graphite anodes. However, these materials face challenges such as a higher operating voltage (1.0–1.8 V *vs.* Li^+/Li), significant voltage losses, and a large amount of energy lost in the first use, which makes it difficult to achieve high energy density. In contrast, alloy-based anodes are seen as more promising for high-energy storage due to their higher capacities and lower operating voltages. Batteries with a Li metal anode are showing great promise for practical use. Li metal has the

advantage of a very low operating voltage of 0 V (*vs.* Li$^+$/Li) and high capacity. However, using Li metal also brings challenges, particularly with stability, as illustrated in Fig. 2 [26].

To tackle the challenges with lithium metal anodes, several approaches have been studied, focusing on strategies like designing SEI films and modifying substrates and separators [27]. These efforts aim to control lithium dendrite growth and enhance safety. A key strategy involves forming a protective SEI layer to stabilize the interface. For instance, Yang *et al.* [28] developed a 3D copper foil with a tiny structured skeleton that holds lithium without uncontrolled dendrite growth, achieving a long cycle life of 600 hours. In carbon-based materials, research on a nitrogen-doped graphene electrode has shown its effectiveness in controlling lithium nucleation and reducing dendrite growth. Zhu *et al.* [29] proposed a unique Li-carbonized metal-organic framework (Li-cMOFs) hybrid anode. In this design, molten lithium metal is contained within a 3D porous structure that uses zinc clusters to stabilize lithium anodes. Similarly, Yoo *et al.* [30] created a polyrotaxane-incorporated poly (acrylic acid) as a binder for carbon nanotube networks. This material helps maintain the structural integrity of the carbon nanotubes–Li anode throughout battery cycling, effectively managing the stress during continuous lithium plating and stripping.

To sum up, battery performance and safety are greatly compromised due to lithium plating caused by rapid charging, which is a major obstacle to achieving fast charging. Studies have shown that taking breaks after undergoing high-current cyclic aging tests can help lessen battery degradation. This is believed to be due to the reactivation of the passivated metallic lithium plating. Waldmann *et al.* conducted research on how rest periods influence the safety of lithium-ion batteries post-lithium plating. Results from the accelerated rate calorimetry test indicate that batteries with longer rest periods after lithium plating take more time to reach thermal runaway compared to those with shorter rest periods, although both take less time than fresh batteries [31]. This suggests that the rest periods allow for the metallic lithium to be chemically re-integrated into the graphite, reducing lithium plating. In summary, integrating reversibly plated lithium back into the anode can diminish capacity loss. Moreover, utilizing microcurrent discharge helps in removing lithium deposits. Nevertheless, these two methods are not applicable in real-time for battery management systems. Hence, real-time quantitative monitoring of plated lithium amounts and the chemical reintegration of plated lithium metal is essential. Techniques such as in-situ methods, voltage relaxation profile analysis, and electrochemical models are promising in this regard. They offer a way to decrease lithium plating and optimize further charging.

Notably, the surface coating creates a protective passivation layer on the electrode, preventing direct contact with the electrolyte. The coated anode's excellent rate performance is due to its superb conductivity and intercalation kinetics. Additionally, the electrode's morphology plays a crucial role in the rate capability of LIBs. For instance, porous graphite, used as an anode material, could enhance the rate capability by facilitating Li$^+$ ions transport.

III. EVALUATION OF MATERIAL AND ELECTROLYTE INNOVATIONS

This section mainly discusses the impact of common cathode materials, electrolytes, and anode materials on the performance of LIBs, focusing on the types and structures of these components. The discussion includes the existing limitations of cathode and anode materials and electrolytes in LIBs. Additionally, it covers the enhancement of these materials and electrolytes through surface modification and doping, ultimately aiming to improve the energy density and charging speed of LIBs.

A. Advances in the Design of Cathode Material for LIBs

1) Advances in the design of high-energy cathode materials

Improving the stability of material structures, especially the surface stability, is crucial for enhancing the overall performance of lithium-ion battery cathode materials. Methods such as elemental doping, interface modification, and composite modification play a vital role in this enhancement. For instance, Liu et al. enhanced the overall electrochemical performance of LIBs by co-doping with Na$^+$ and F$^-$. This approach combines the benefits of Na doping for greater structural stability and F$^-$ doping for improved electrical conductivity. As a result, the modified sample maintained 100% of its capacity after 100 cycles at 0.2C [16]. Liu *et al.* also improved surface stability through surface delithiation with Na$_2$S$_2$O$_3$, which activated the surface and induced a significant enrichment of Ni elements. This modification led to a better capacity retention rate of 89.2% after 250 cycles at 1C [32]. In another study, Ji *et al.* coated Li-rich layered oxide (LLO) cathodes with LiMn$_{1.4}$Ni$_{0.5}$Mo$_{0.1}$O$_4$ while also doping with Mo^{6+}. The Mo^{6+} doping increased lattice parameters and strengthened the transition metal ions interaction, which effectively inhibited oxygen release and mitigated Jahn-Teller distortion caused by Mn^{3+} dissolution. Moreover, the LiMn$_{1.4}$Ni$_{0.5}$Mo$_{0.1}$O$_4$ coating protected the LLO cathodes from electrolyte corrosion, enhancing structural stability and improving the capacity retention rate to 66.8% after 200 cycles at 0.1C[33].

2) Advances in the design of fasting-charging cathode materials

Improving the ionic and electronic conductivity of cathodes offers a lot of potential for fast charging. When charged at high currents, the lithium concentration in the electrode can cause more stress, especially when the temperature is not even. This stress can damage the cathode, leading to issues like particles breaking apart, layers separating, or cracks between the particles and the things that hold them together. Bigger particles or faster charging rates make these breaks more likely. When the particles break, the electrode does not work as well, and it can also react badly with the fluid in the battery, causing even more damage. In fact, this fluid can get into the cracks and mess up how the current flows, causing more cracks. Therefore, smaller particles tend to be safer as they do not have as much stress from the lithium.

Compared to anodes, cathode materials with the ability to handle high rates are known for quick Li$^+$ removal and stable cycling. Making lithium pathways short and ensuring high

ionic conduct are among the strategies for optimizing them. Table 2 provides a summary analysis of typical strategies to enhance the cathode's rate ability. The ability of anode materials to enhance the rapid charging capabilities of lithium-ion batteries primarily involves Surface coating, Gradient structure, doping, and physical method. For example, surface coating is one of the ways to help the cathode's rate capability. Graphene-coated $LiNi_{1/3}Co_{1/3}Mn_{1/3}O_2$ shows great ability at high current densities. The active materials formed by graphene sheets aid in charge transfer ionic transport and reversibility. Additionally, cathodes with a surface coating also offer impressive high-rate performance by boosting interfacial kinetics. As an instance, ZrO_2-coated $LiNi_{0.5}Mn_{1.5}O_4$ shows improved cycle stability at a 6C charging rate, due to reduced charge transfer resistance, which improves the interfacial kinetic. Composite cathode materials can achieve high-rate capability due to their optimized electrochemical properties and layered structure. The independent $LiFe_{0.2}Mn_{0.8}PO_4$ (LFMP)/rGO nanocomposite demonstrates impressive stability throughout its cycles under high-rate charging, a characteristic credited to its 83wt% load of active material. The airy structure of LFMP nanoparticles also minimizes tortuosity. When structured with a gradient, cathode materials uphold excellent retention of capacity at elevated current densities, thanks to their enhanced electrochemical properties compared to their intrinsic material.

Table 2. Analysis of typical strategies for rate capability improvement in the cathode.

Strategies	Description	Advantage	Conclusions
Surface coating	Modified the $LiNi_{1/3}Co_{1/3}Mn_{1/3}O_2$ cathode with uniformly dispersed graphene nanosheets [34]	Improves electronic conductivity	88.2% of initial capacity after 400 cycles (1C)
Gradient structured	Concentration-gradient shell encapsulated $LiMn_{1.91}Ni_{0.072}Co_{0.016}O_4$ [35]	Reduces the polarization and inner resistance	96% of initial capacity after 200 cycles (1C/55 ℃)
Gradient structured	Fabrication of $LiNi_{0.8}Co_{0.1}Mn_{0.1}O_2$ cathode with full-gradient structure [36]	Improves the Li^+ diffusion coefficient	93.7% of initial capacity after 100 cycles (5C)
Doping	Fabricated the $Li(Mn_{1/3}Ni_{1/3}Fe_{1/3})O_2$–Polyaniline composite cathode [37]	Improves the electronic conductivity	86% of initial capacity after 40 cycles (15C)
Doping	Fabrication of $LiFePO_4$ cathode with redox-active fluoflavin polymer [38]	Decreases the electrode resistance	Ultrafast output (>20 mA cm^{-2} at 30C)
Physical method	Exposure of light to an operating $LiMn_2O_4$ cathode[39]	Reduces the energy required for Li^+ delithiation	Double the charging speed

For example, Wen *et al.* created a new $LiMn_{1.912}Ni_{0.072}Co_{0.016}O_4$ cathode surrounded by a concentration-gradient shell. This was identified by an increasing presence of Ni and Co and a decreasing presence of Mn towards the particle surface. Furthermore, electrochemical tests highlighted its improved rate capabilities [35].

B. Improving Electrolyte

1) Advanced electrolytes for high-energy LIBs

To meet the high energy density demand of lithium batteries, extensive research has been conducted on high-voltage electrolytes, focusing on enhancing their electrochemical stability and tolerance to redox reactions. By optimizing the structure of the electrolyte and incorporating appropriate additives, the decomposition of the electrolyte and oxidation of electrode materials can be suppressed. The SEI film, formed on the electrode surface by high-voltage electrolytes, is a critical factor affecting battery performance and stability. Adjusting the electrolyte components or introducing additives can improve the interaction between the electrolyte and electrode materials, leading to a stable SEI film and reducing side reactions as well as the capacity fade of lithium batteries. High-voltage electrolytes also set higher tolerance requirements for battery materials. Researchers are working on developing new electrolyte materials to enhance their tolerance and stability against high-voltage electrolytes.

Solid electrolytes, with their high-temperature resistance, non-flammability, and leak-proof nature, are considered among the most promising candidates for high-performance electrolytes in lithium batteries. This includes Polyethylene Oxide (PEO), Polyacrylonitrile (PAN), and polyvinylidene fluoride. Solid Polymer Electrolytes (SPEs) offer advantages like thermal stability, mechanical strength, and cost-effectiveness. However, their low ionic conductivity at room temperature and interface instability at high voltages hinder their application. Practical enhancements can be achieved by doping with nanoscale inorganic metal particles, selecting lithium salts with high ionic conductivity, or blending with other polymers to lower the phase transition temperature, thereby improving ionic conductivity. Additionally, interface stability can be improved by modifying the molecular structure through the introduction of other polymer chains, leading to the formation of supramolecular copolymers, amorphous copolymers, and block copolymers.

The composite of inorganic-polymer solid electrolytes can significantly enhance the ionic conductivity in lithium batteries, thereby boosting their energy density. They were inspired by the similarity between H-bonds and Li-bonds. Zhang *et al.* employed in-situ coupling technology and used commercial 3-chloropropyltrimethoxysilane (PDMS) as a coupling agent to facilitate the chemical bonding interaction between Polystyrene (PS) and Polyethylene Glycol (PEG). Subsequently, poly (ethylene oxide) (PEO) and LiTFSI were added to obtain a uniform composite solid electrolyte. This composite showcased high ionic conductivity and high Li^+ transference number, effectively suppressing the growth of lithium dendrites. This work offers new strategies for enhancing the energy density of lithium batteries [40].

2) Advanced electrolytes for fasting-charging LIBs

Amounts of studies have demonstrated that electrolyte additives can improve the rate capability and reduce degradation in batteries. This improvement mainly comes from better conductivity and faster ion transport, due to lower charge transfer resistance. Electrolyte additives also help to change the properties of the SEI, making it more beneficial

for Li$^+$ intercalation kinetics. For example, adding isothiocyanate to lithium hexafluorophosphate-electrolyte helps to get rid of harmful species like HF and PF$_5$, this results in more stable and ion-friendly interfacial layers. Furthermore, electrolyte additives with high reduction potential, such as Fluorosulfonyl Isocyanate (FI), enhance the battery's performance at high rates. FI is reduced before the carbonate-based electrolyte, forming a conductive SEI and lowering the interfacial resistance. On the other hand, enhancing the rate performance of LIBs at low temperatures is crucial. Allyl sulfate, as an electrolyte additive, boosts the rate capability of the graphite anode at low temperatures. This is due to a carbon-rich sulfur-containing film that enhances the charge transfer reaction. Besides electrolyte additives, using highly concentrated electrolytes with a high salt concentration also shows promise in improving rate performance. These electrolytes contribute to better rate capability through a high transference number of t$_+$, high Li$^+$ concentrations at the interface, and an effective ion-conducting SEI. Moreover, the solvated structure in highly concentrated solutions can facilitate Li$^+$ transport through a ligand exchange reaction, speeding up Li$^+$ conduction. For instance, Acetonitrile-based electrolytes not only provide improved reductive stability but also enhance the Li$^+$ transference number t$_+$ and the intercalation kinetics of reversible lithium.

Boosting the Li$^+$ transference number t$_+$ in electrolytes enhances the rate capability and power density of LIBs. This is particularly important for fast charging processes, such as those exceeding 2C. Essentially, the amount of ionic current that Li$^+$ can carry is directly linked to the Li$^+$ transference number t$_+$. As a result, a higher State Of Charge (SOC) can be achieved before hitting the cutoff voltage, maintaining constant conductivity. There are several strategies to improve the Li$^+$ transference number t$_+$. These include developing electrolytes with high Li$^+$ transference numbers, using nonaqueous polyelectrolyte solutions as liquid electrolytes, and employing super-concentrated electrolytes. Additionally, using novel Li salts with larger 'bulky' anions can increase the transference number, though it may reduce ionic conductivity. Ultimately, the goal is to create an electrolyte that balances high ionic conductivity with a high ion transfer number, particularly for fast-charging applications.

New electrolyte solutions that exhibit high ionic conductivity and chemical stability have shown promising results in enhancing rate performance. For instance, using innovative organic co-solvents with a low viscosity can lead to an increase in both ionic conductivity and the lithium transference number t$_+$. Introducing ester co-solvents proves beneficial for boosting ionic conductivity and improving rate capability, especially at low temperatures. However, it is crucial to carefully balance the lithium salt/solvent ratio to maintain a good trade-off between enhanced conductivity and prolonged cycling lifetime. Furthermore, it is important to emphasize the need for improving electrolyte conductivity across various temperature ranges. Table 3 presents a detailed analysis of common strategies employed to boost the rate capability of electrolytes.

Table 3. The improvement methods of the rate capability of electrolytes.

Strategies	Description	Advantage	Conclusions
Electrolyte additives	Additive the isothiocyanate in LiPF$_6$-based electrolytes to scavenges HF and PF$_5$	Reduces the R$_{SEI}$	91.8% of initial capacity after 300 cycles (2C)
	Additive the LiPF$_6$ in dual-salt/carbonate-solvent-based electrolytes	Forms a stable and conductive SEI	97.1% of initial capacity after 500 cycles (1C)
	Additive the diphenyl sulfone in EC/EMC/DEC (1:1:1)	Improves lithium-ion transport	75% of initial capacity after 500 cycles (5C)
	Additive the Non-aqueous LiPO$_2$F$_2$ in EC/DMC (1:1)	Reduces the R$_{SEI}$ and R$_{et}$	95.7% of initial capacity after 800 cycles (1C)
Highly concentrated electrolytes	Superconcentrated lithium bis(fluorosulfonyl)amide	Improves the Li$^+$ intercalation and transference number t$_+$	The anode recharged 70% SOC within 30 mins
	Superconcentrated Acetonitrile solutions	Increases the Li-ion transference number t$_+$	Enhanced the rate capability at various C-rates (C/20 -5C)
Novel solvent compositions	Methyl formate	Increases the ionic conductivity	Optimal rate capability and cycling lifetime
	Dimethyl carbonate	Increases the ionic conductivity	88.7% of initial capacity after 200 cycles (4C)
	Lithium is(fluorosulfonyl)imide	Improves conductivity and Li-ion transference number t$_+$	84% of initial capacity after 500 cycles (5C)

In sum, employing low-viscosity co-solvents, high-concentration electrolytes, and additives that lead to desirable SEI properties is a beneficial strategy to enhance the rapid charging of lithium-ion batteries. It is crucial to underline the need for a detailed assessment of both the rate capability and the lifetime in electrolyte studies. Most investigations into these modified materials and design methods, including electrodes and electrolytes, occur at the laboratory level. These findings might not consistently translate to advancements in commercial batteries. Consequently, collaborative efforts from various disciplines are essential to promote the rapid charging technology in LIBs.

C. Anode Materials for High-energy and Fast-charging Strategies Advancement

To reduce lithium plating at high current densities and boost energy density, it is believed that enhancing the fast-charging capabilities of lithium batteries is feasible by preparing anode materials through elemental doping and composite modification. Wu *et al.* conducted a study on Sulfurized Polyacrylonitrile (SPAN) as an anode material. Their findings indicate that SPAN's higher lithiation potential contributes to outstanding cycling stability, especially at high C-rates [41]. Additionally, introducing trace amounts of certain chemical elements into anode materials can optimize their microstructure and charge state, benefiting the rate capability. A prime example is the Ge-doped Li$_4$Ti$_{4.95}$Ge$_{0.05}$O$_{12}$ with a cubic spinel structure. This modification not only significantly reduces the particle size but also improves the rate capability. These enhancements are due to better intercalation kinetics and a

shorter path for Li^+ diffusion. Liu *et al.* developed a dendrite-free, dual-skeletons, three-dimensional Li-B-Sn composite lithium anode using a melting method. Furthermore, batteries assembled with a $LiFePO_4$ cathode (~11 mg cm^{-2}) and the Li-B-Sn composite anode exhibited excellent electrochemical performance. After 430 cycles, they maintained a high capacity retention rate of 92.5% at 2 ℃ [42]. Zhai synthesized a lithium-rich alloy composed of metallic Li and $Li_{22}Sn_5$, which was shown to control the volume changes of Li. This is attributed to the $Li_{22}Sn_5$ framework, which offers good electrical conductivity, rapid lithium ion diffusion, and excellent lithiophilicity. These properties allow for the conformal deposition of Li [43].

Besides the properties of the battery material, the surface capacity of the electrode plays a crucial role in the battery's rate capability. For various applications, it is necessary to adjust the C/A capacity ratio in commercial LIBs based on the properties of the electrodes. Generally, a higher C/A ratio indicates a shortage of available intercalation sites for Li^+, which could lead to lithium plating, especially during high-current charging or at low temperatures. On the other hand, a lower C/A ratio helps prevent lithium deposition but may cause the cathode to overcharge. Furthermore, enhancing the anode's active surface area and porosity can improve the battery's charging speed. Reducing the thickness of the electrode and enhancing its porosity can improve the battery's charging speed, as these changes help Li^+ ions move more easily through the porous electrode. The ideal electrode thickness for high charging rates is generally thinner than the standard thickness. However, making the electrode thinner can lead to a decrease in energy density. Additionally, a new type of anode with larger pores and a higher specific surface area can shorten the travel distance for lithium ions, showing promise for further improvements in charging speed.

IV. CONCLUSION

For a long time, range anxiety and prolonged charging times have hindered the widespread adoption of EVs. The development of high-energy-density lithium batteries and fast charging technologies has made EVs more convenient, emerging as a promising research area. Strategies to enhance the energy density and charge rate of lithium-ion batteries involve improvements in cathode and anode materials, as well as electrolyte optimization. Fast charging of LIBs faces several challenges: (1) lithium plating, a primary degradation mechanism in graphite anodes, leading to significant capacity loss; (2) mechanical fracturing due to stress mismatch among components during rapid charging, impacting battery performance and hindering ion transport; (3) heat generation during fast charging can cause side reactions and potentially lead to thermal runaway, posing serious safety concerns. Essentially, enhancing lithium-ion battery energy density and charging speed involves a multi-scale approach, such as improving electrode performance, enhancing interface kinetics, and shortening ion diffusion distances. Achieving electrolytes with excellent migration dynamics and chemical stability is crucial.

At the electrode level, enhancing performance improves interface kinetics and shortens diffusion distances. (1) For anodes, challenges include addressing lithium plating in graphite anodes and managing silicon particle expansion in silicon-based anodes, as well as safety concerns with lithium dendrite formation in lithium metal anodes. (2) Cathode materials, such as $LiCoO_2$, advanced nickel-rich, and lithium-rich manganese oxides, exhibit stable structures and fast internal ion transport. However, degradation through oxygen release, transition metal dissolution, and interface instability, leading to capacity loss and shortened life cycles, can be mitigated by ion doping and surface coating strategies. (3) Regarding electrolytes, their composition directly affects SEI performance. Additives in electrolytes help form dense, stable SEIs with high ionic conductivity, meeting fast-charging requirements. Innovations like high-concentration and localized high-concentration electrolytes primarily improve battery performance by altering Li^+ solvation structures and curbing continuous electrolyte decomposition. Solid electrolytes show immense safety advantages, though their ion transport rates need further enhancement.

In summary, to meet the growing demand for fast-charging EVs, intensified research on high-energy-density and fast-charging LIBs, particularly in electrode materials and electrolytes, is essential. Achieving excellent battery performance requires ensuring rapid Li^+ diffusion in both anodes and electrolytes, reducing kinetic barriers in SEIs. Inadequate Li^+ transport kinetics can lead to significant polarization, causing anode lithium plating, reducing battery life, and raising safety concerns. The SEI layer, mainly composed of electrolyte decomposition products, significantly influences fast-charging performance. Thus, optimizing anodes and electrolytes is crucial for fast charging. Moreover, achieving high energy density, safety, and stability in fast charging under extreme conditions poses stringent demands on battery systems and material design. To achieve the goal of fast-charging lithium-ion batteries, it is essential to comprehensively consider the optimization of battery structure and components. This approach addresses the various challenges associated with fast-charging conditions and lays the foundation for the widespread commercial use of these advanced batteries. Such advancement will support the high-quality, sustainable development of the EV industry, contributing to global goals of peak carbon emissions and carbon neutrality.

CONFLICT OF INTEREST

The author claims that no conflict of interest exists.

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