Advanced Lithium Batteries and Fast-Charging Technology: Challenges and Future Directions

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Abstract. Lithium-ion batteries (LIBs) are essential for advancing electric vehicles (EVs) and consumer electronics, offering high energy density and fast-charging capabilities. Nanotechnology, like incorporating polyaniline-modified graphene composites (PMGCs), has significantly enhanced ion diffusion and electron conductivity. However, key challenges persist, including thermal management, solid electrolyte interphase (SEI) layer growth, and charger compatibility. Safety concerns, such as thermal runaway caused by ohmic losses, underscore the need for advanced battery management systems (BMS) and innovative electrolytes. Solid-state batteries (SSBs) present a promising future with higher safety and energy density, yet they are still under development. During the transition, optimizing LIBs through material improvements and charging technologies will be vital to maintaining their market dominance. Enhancing safety measures, including better BMS and more stable electrolytes, is crucial for the continued application of LIBs in EVs, portable devices, and other high-demand sectors. These strategies will ensure LIBs remain competitive until SSBs are commercially viable.

Keywords: Lithium-ion battery; fast-charging technology; solid-state battery.

1. Introduction

The widespread application of lithium-ion batteries (LIBs) used in portable electronic devices, not only electric vehicles (EVs), but also computers and smartphones [1]. The benefit of LIBs is high energy density and are characterized by the reversible intercalation/deintercalation of Li ions between electrodes. The rapid advancement of LIBs technology has improved production efficiency and reduced costs for manufacturers, driving higher demand for batteries and expanding their use across various industries, especially in a wide range of vehicles. Fast charging is important for multiple applications, like EVs, computers and smartphones. The principles are based on shortening lithium-ion diffusion and increasing electron conductivity. To achieve this achievement, nanotechnology plays a significant role in most materials. To consider cost-effectiveness, the utilization of polyaniline-modified graphene composites (PMGCs) can enhance the performance [2].

In contrast, much heat is released during the charging and discharging process. To ensure safety and avoid thermal runaway, a battery management system (BMS) is needed to heat efficiently. In addition, during the charging process, solid electrolyte interphase (SEI) gets thicker in the electrode, reducing the battery lifespan. Changing the materials of the electrode and boosting the state of the electrolyte, can mitigate this problem. Solid-state batteries (SSBs) can be expected to reduce charging time and foster the life cycle in the future, but there is a long way for SSBs from the laboratory to large-scale application and commercialization. There are various challenges to the performance of SSBs, such as low ion conductivity [3]. Compared to the SSBs, LIBs are the main technology used in the EV market now due to their cost and durability. The article discusses how lithium battery technology can improve fast charging capacity, prolong life, and improve safety during the transition period and predicts the significance and replacement timing of SSBs in these improved technologies.

2. Fundamentals of LIBs

2.1. Composition and Structure of LIBs

The composition and structure of LIBs included a cathode, anode, separator and electrolyte [4]. Cathodes, such as $LiCoO_2$ and $LiFePO_4$, lose electrons in anodes, such as graphite and silicon-based materials. Electrolytes carry out the ions diffusion, releasing from the electrodes. The separator refers to separate electrodes, avoiding a temporary short circuit.

2.2. Working Principles of LIBs

The mechanism of LIBs is indicated in it, using a $LiCoO_2$/graphite cell as an example. As shown in Fig. 1, during the charging process, external electrical energy is applied, forcing lithium ions to leave the cathode ($LiCoO_2$) and diffuse to the anode (graphite). In the cathode, an oxidation reaction occurs as the electrode is released into the external circuit. Lithium ions (Li^+) are extracted from the $LiCoO_2$ structure, and cobalt undergoes a transition from the oxidation state of Co^{3+} to Co^{4+}. Lithium ions migrate through the electrolyte and enter the anode. The formation of the SEI on the exterior of the anode provides a protective layer, which can reduce the battery's overall capacity. At the anode, the lithium ions are reduced to lithium atoms through intercalation. Lithium ions combine with carbon atoms to form a stable structure, which is stored in the electrode. During the discharging process, electrons are transferred from the anode to the cathode due to the high conductivity of the latter and the presence of a number of electrons in the former. This transfer is known as the Domino effect.

$$\text{Cathode reaction: } LiCoO_2 \rightarrow Li_{(1-x)}CoO_2 + xLi^+ + xe^- \quad (1)$$

$$\text{Anode reaction: } 6C + xLi^+ + xe^- \rightarrow Li_xC_6 \quad (2)$$

$$\text{Reaction: } LiCoO_2 + 6C \rightarrow Li_{(1-x)}CoO_2 + Li_xC_6 \quad (3)$$

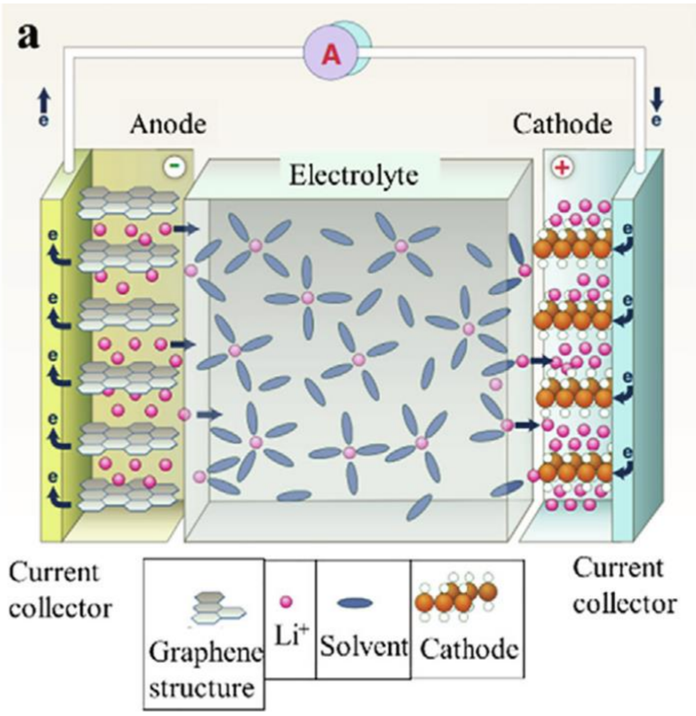

Fig. 1 The working mechanism of $LiCoO_2$/graphite cell [4].

3. Fast-Charging Technology for LIBs

The ability to charge electronic devices rapidly is a crucial aspect of next-generation energy storage systems. A higher rate of current movement and larger voltage can achieve fast charging performance. The use of nanomaterials can facilitate the movement of lithium ions in electrodes, thereby reducing charging time and enhancing the efficiency of the charging process. As shown in Fig. 2, exemplified by the use of Li_3VO_4 materials in the anode.

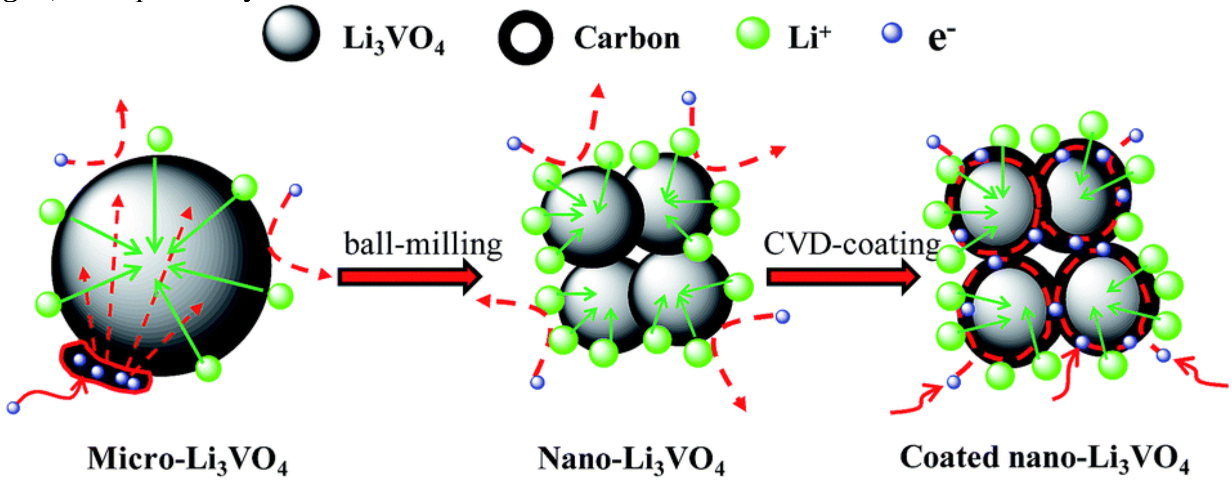

Fig. 2 The cases of lithium-ion diffusion and electron conduction in micronized Li_3VO_4, nanosized Li_3VO_4, and fully carbon-coated nanosized Li_3VO_4. The green solid arrows and red dashed arrows illustrate the lithium-ion diffusion paths and electron conduction paths, respectively [5].

The Li_3VO_4 is pulverized into particles of a nanoscale, which serve to abbreviate the distance that the Li^+ ions must traverse in order to reach the interior and surface of the material. This results in a more rapid charging and discharging process.

Furthermore, the particle surface was uniformly coated with a nanolayered carbon layer, enhancing the conductivity of the electrode and reducing the internal resistance to electron transport, thereby increasing the efficiency of the charging process. As a consequence, the first Coulombic efficiency increased from 68.8% to 79.5%, and the reversible capacity increased from 225 to 315 mA h g^{-1} [5].

Choi et al. put forward a strategy for the fabrication of the positive electrode with well-dispersed carbon nanotubes (CNTs), which involves controlling the solid content and the sonication process of the slurry using $LiNi_{0.8}Co_{0.1}Mn_{0.1}O_2$ as the cathode material [6]. However, these approaches are confronted with challenges pertaining to cost and aggregation issues. Polyaniline (PANI), a cost-effective, stable and conductive polymer, was investigated [2]. In Fig. 3, The formation of PMGCs was achieved through the utilization of ammonium persulfate (APS) as an oxidant during the polymerization of PANI, simultaneously serving as a surface modifier for graphene.

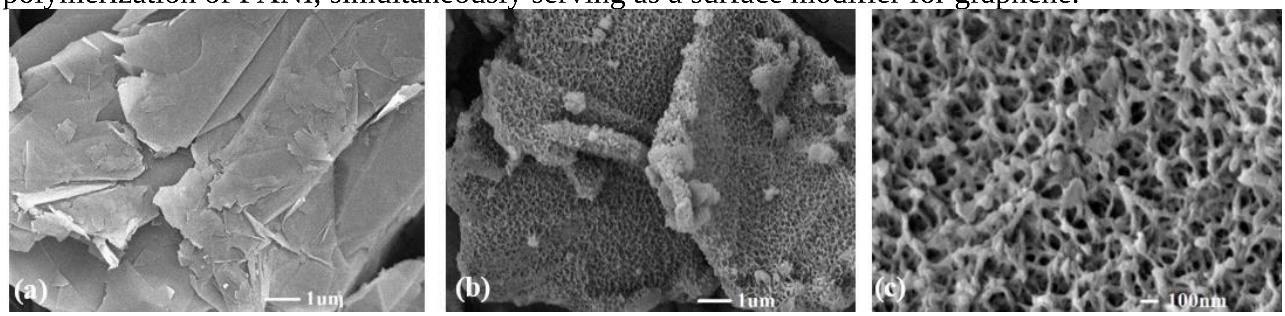

Fig. 3 SEM images of (a) pure graphene, (b) PMGC, and (c) higher magnification image of (b) PMGC [2].

The impact of these variations was assessed in terms of reductions in internal resistance, aging effects, different charge and discharge rates, and cycle performance. The performance of two types of batteries was compared: C0.5A0 Battery (G2), which had 0.5% PMGCs added to the cathode electrode, and Control Group (C0A0, G1) without PMGCs [2].

The incorporation of PMGCs demonstrably enhances the efficiency and speed of the charging process, thereby illustrating the potential of this approach to markedly enhance the overall performance of battery systems, as evidenced in Table 1.

Table 1. The charging capacity of C0A0 and C0.5A0 under different constant currents [2].

Sample	1 C	2 C	3 C	5 C
C0A0 (mAh)	3130	2567	1879	350
	100%	82%	60%	11%
C0.5A0 (mAh)	3311	2979	2650	476
	100%	90%	80%	14%

4. Key Challenges

4.1. Safety Issues

The electrodes, current collectors and electrolytes that comprise the battery have a specific resistance. As an electric current passes through the battery, the resistance generates heat, which is referred to as ohmic loss. The quantity of heat generated is directly proportional to the square of the current ($Q = I^2R$). Thus, the resistance within the battery causes an increase in heat generation during high-current fast charging [7]. There are various reasons for the incidence, as shown in Fig. 4. Consequently, the thermal management of such a large battery pack represents a significant challenge in ensuring battery safety. (1) The collision process causes the battery to squeeze, and the area with strong stress is damaged, resulting in the internal short-circuit or the casing rupture, which can cause thermal runaway of batteries. (2) During the abused charging process, the heat generation is too late to diffuse, resulting in heat accumulation inside the battery, leading to thermal runaway of batteries. (3) During the operation of the battery, if the heat generated is too late to diffuse, it is easy to cause the battery thermal runaway. (4) When the battery receives a local thermal shock, it is easy to cause the battery to catch fire. The fire of an electric vehicle will cause the burning of electric vehicles in the nearby area.

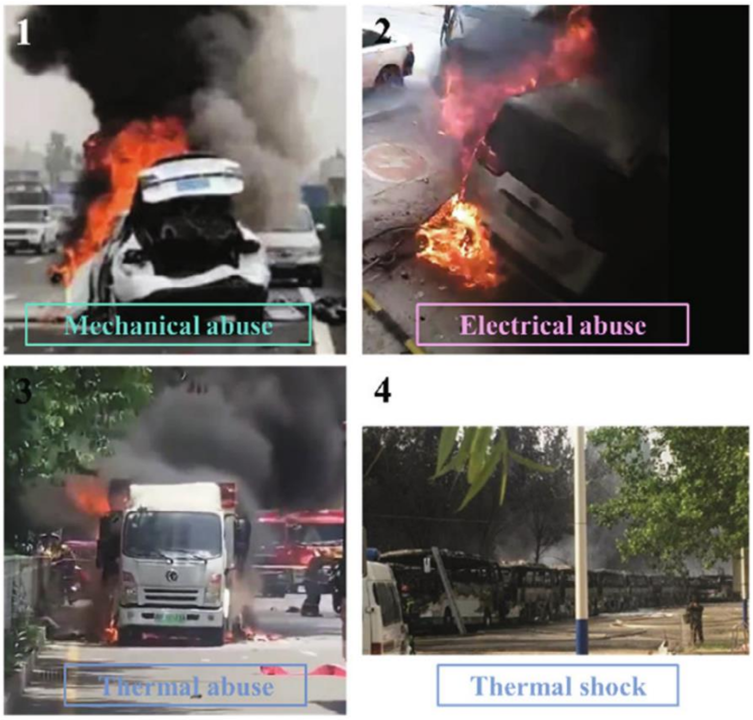

Fig. 4 Collision (mechanical abuse), charging (electrical abuse), self-ignition (thermal abuse) and thermal shock (thermal abuse) caused electric vehicle fires [8].

4.2. Degradation of Battery Materials

According to Fig. 5, during the discharge phase, the reduction in particle size and the maintenance of a stable SEI layer thickness result in the generation of stress, which ultimately leads to the formation of cracks in the SEI. Upon recharging, a new SEI layer is formed. The repeated cycles of this process result in the continuous growth of the SEI layer over time.

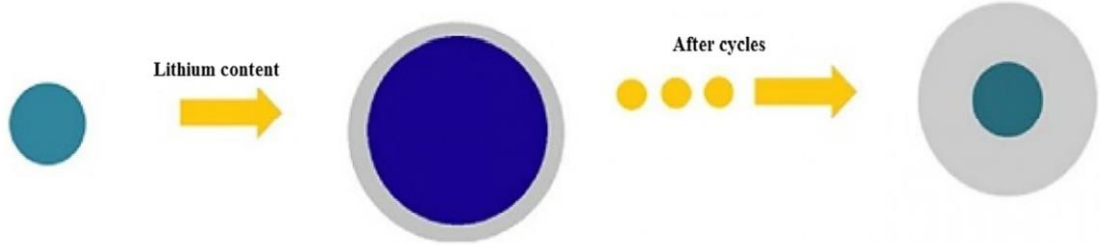

Fig. 5 How the SEI layer grows [9].

Therefore, the SEI would reduce the capacity of the anode during the charging process, contributing to less life cycle. There is a challenge to balance the battery capacity and long lifespan.

4.3. Compatibility of Chargers and BMS

In order to facilitate the process of home charging, a significant number of electric vehicles are designed with the capability to be plugged into a standard household alternating current (AC) outlet, thus enabling the charging of the vehicle to be completed overnight. The methods for achieving this vary considerably. They range from a basic cord that links the car to a power source to more advanced systems, such as IC-CPD, which integrate control and safety features within the charging cable itself. Alternatively, there are wall-mounted charging stations that offer advanced features, including two-way communication between the vehicle and the charger, along with integrated grounding and safety mechanisms. However, the vehicle's battery requires direct current (DC) power for charging, necessitating the conversion of AC power to DC through the vehicle's onboard charging system. This configuration requires that each vehicle be equipped with a charging system that must balance various factors, including cooling, efficiency, and weight. These elements can limit the charging rate and, consequently, the speed at which the battery charges. A more promising solution is the development of standardized, offboard DC charging stations that could potentially offer faster and more efficient charging options [10].

5. Future Directions

5.1. Strategies for LIB Safety Improvements

The safety of batteries is contingent upon a number of factors, including the chemical composition of the active materials and electrolytes, the rate of heat production and removal, and the resistance to mechanical stress. In the initial stages of assessment, it is advisable to focus on the materials employed in the electrodes, the electrolyte, and the separator, as these components can be most readily controlled. Additionally, strategies must be incorporated into the design of LIBs that can mitigate the effects of potential thermal and electrical misuse. Moreover, it is advisable to conduct safety tests on newly manufactured LIBs prior to their utilization in any devices, as a consequence of the fact that the generation of heat and gas as a result of parasitic reactions represents the primary cause of safety incidents in LIBs, the enhancement of battery safety should prioritize the prevention of overheating, the assurance that the batteries operate within an appropriate voltage range and the improvement of their cooling capabilities [8].

5.2. New Electrolyte

SSBs employ a solid electrolyte in place of a liquid one, enabling faster charging without the associated risks of thermal runaway. The advantages of SSBs are that they are safer than traditional lithium batteries since the cooling system is crucial to managing the heat produced during charging. The anode can be made from lithium metal or silicon, but neither material can achieve the same energy density as LIBs. The presence of a SEI incorporating lithium fluoride (LiF) is of great consequence in the enhancement of lithium metal batteries (LMBs), largely due to its exceptional stability and mechanical strength. However, the relatively low ionic conductivity of LiF may impose a limitation on the rate at which lithium ions can traverse the SEI layer [3]. In the case of a lithium metal anode, the formation of Li dendrites is an unavoidable electrochemical phenomenon caused by the repeated stripping and uneven deposition of Li ions on the surface [11]. Cronau et al. illustrated that for advanced secondary (rechargeable) sodium batteries (ASSBs) that utilize carbon-based anodes with a deposition mechanism, the battery's discharge capacity can be substantially enhanced through two primary methods [12]. Firstly, by actively managing the pressure within the battery stack, and secondly, by applying heat and pressure to the anode and separator that contain the binder. As a result, SSBs demonstrate an increased discharge capacity, While approach (i) is readily applicable for use in laboratory settings, approach (ii) offers a promising avenue for future commercial ASSBs [12].

6. Conclusion

PMGCs would replace the CNTs used in the electrode to consider the cost-effectiveness of materials in EVs. The safety and longevity of batteries, particularly within the context of electric vehicles, are contingent upon a multitude of factors, the influence of which can be complex and varied. Effective thermal management is a crucial aspect in the prevention of thermal runaway.

In addition, the deterioration of battery materials, particularly SEI, represents a significant factor influencing battery lifespan, emphasizing the necessity for strategies that achieve a balance between high capacity and extended battery life.

Furthermore, ensuring compatibility between chargers and BMS is of paramount importance for safe and efficient home charging. While various methods exist to facilitate this, the necessity for AC to DC conversion onboard the vehicle presents challenges in terms of efficiency and charging speed.

The development of solid-state batteries is regarded as a significant area of focus for the advancement of rapid charging technology, given their enhanced energy density and superior safety characteristics. Nevertheless, SSBs are still in the research and development phase and at an early stage of commercialization, with a significant gap between them and the point of large-scale adoption. In the context of the prevailing technological and market landscape, traditional lithium batteries continue to represent the predominant choice in a range of applications, including electric vehicles and consumer electronics. This indicates that lithium batteries will continue to be the dominant technology in the near term, while solid-state batteries represent the future direction. Therefore, it is essential to investigate how to enhance the performance of existing lithium battery technology through material improvement and fast charging technology optimization in order to maintain lithium batteries' market dominance. Concurrently, it is crucial to examine the technical limitations that solid-state batteries may overcome in the future and their potential in fast charging technology.

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