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Research Progress of Anode Material for Lithium-ion Batteries

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Abstract. Against the backdrop of global energy transition and carbon neutrality goals, lithium-ion batteries are receiving increasing attention due to their high efficiency and large capacity storage advantages. This study systematically evaluated four mainstream positive electrode materials - $LiMn_2O_4$ (LMO), $LiCoO_2$ (LCO), $LiFePO_4$ (LFP), and ternary materials. These materials have their own characteristics: LMO has low cost and good safety, but its performance may decrease in high-temperature environments; LCO has a high energy density, but is limited by the scarcity and thermal stability of cobalt resources; LFP has outstanding safety and long cycle life, but low energy density; Ternary materials exhibit excellent energy performance, especially suitable for low-temperature environments, but require high thermal management technology. The research results can help match material types according to specific needs, reduce dependence on key raw materials, enhance the sustainability of the battery industry, and provide reference for future research and development directions. Finally, this article combines energy security and environmental protection goals, and proposes corresponding suggestions for different application scenarios to promote battery technology to better serve diversified practical needs.

Keywords: lithium-ion batteries, anode materials, development prospects

1. Introduction

Nowadays, the energy crisis has become one of the major challenges that humans face. The Russia-Ukraine conflict has led to a 45% reduction in Europe 's natural gas supply, and global crude oil inventories have dropped to their lowest level in five years. In 2022, the price of Brent crude oil soared from $70 to $130, with significant price fluctuations. The energy usage structure is unbalanced , fossil energy still accounts for most of global energy consumption [1]. Carbon emissions continue to increase, and global CO_2 emissions reached a new high in 2023, causing environmental pressure. Therefore, countries are urgently making an energy transition towards electrification. Electrification can increase efficiency by several times compared to internal combustion engine systems, significantly reduce carbon dioxide emissions, and is closely related to renewable energy. Meanwhile, battery technology is the foundation of electrification. Among various energy storage solutions, lithium-ion batteries have become the dominant technology for automotive applications due to their high energy density, long cycle life, and fast charging capacity. The anode material of lithium-ion batteries is the key factor affecting their performance such as

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energy density, power density, and thermal stability. The anode represents the most crucial component in LIB systems, responsible for: 1.40-50% of total battery cost structure 2.30-40% of overall energy density [2]. Findings about anode will bring benefits in various aspects: when it comes to energy security dimension, the development of anode materials with high energy density and low cost can reduce the reliance on strategic resources such as cobalt and nickel, and alleviate supply chain risks caused by geopolitics; when it comes to carbon neutrality goal, optimizing the thermal stability of anode materials can enhance battery safety and support large-scale grid integration of renewable energy. The breakthrough in solid-state battery technology is expected to reduce the carbon emissions of electric vehicles throughout their entire life cycle by more than 40%; when it comes to industrial economic value, through material innovation (such as single-crystal NCM and nano-coating technology), battery costs can be further reduced by 15%, accelerating the global electrification process. It is estimated that the market size of power batteries will exceed 1.2 trillion US dollars by 2030; when it comes to technology synergy effect, the research on anode materials and the formation technology of emerging battery systems such as sodium-ion and lithium-sulfur are linked to provide solutions for multi-scenario energy storage [3]. Current research on automotive lithium-ion batteries focuses on five key directions: In anode materials, high-nickel ternary (NCM811/NCA) batteries have achieved energy density exceeding 300 Wh/kg, though thermal stability improvements remain necessary. Lithium-rich manganese-based materials demonstrate theoretical energy density over 400 Wh/kg but face voltage decay challenges. Meanwhile, modified lithium iron phosphate (LFP) enables 15-minute fast charging to 80% capacity through nano-structuring, now in mass production.Solid-state battery technology shows breakthrough progress, with TaiLan New Energy and Changan Automobile developing solid-state electrolyte layers thinner than 1 μm, increasing energy density by 30%. CATL has prototyped 500 Wh/kg all-solid-state batteries. Fast-charging advancements include AI-powered algorithms extending cycle life beyond 3,000 cycles, and novel electrolyte additives reducing temperature rise by 40% during rapid charging [4].

This article will focus on the morphology of the anode in lithium batteries, aiming to summarize the characteristics and performance of anode materials with different morphologies, explore their impact on energy storage performance, and offer suggestions for the future development of anode materials, laying a foundation for the research and development of lithium batteries with high energy density and long service life.

2. Preparation anode of lithium-ion batteries

Lithium-ion batteries achieve energy storage and release through the intercalation and de-intercalation of lithium ions between the positive and negative electrode materials. During charging, lithium ions are released from the positive electrode, migrate through the electrolyte to the negative electrode and intercalate. When discharging, lithium ions move in the opposite direction back to the positive electrode, and electrons form a current through the external circuit. According to crystal structure and chemical composition, mainstream cathode materials can be classified into four categories.

2.1. Lithium manganate

Lithium manganate (chemical formula: $LiMn_2O_4$) is an inorganic compound, belonging to the spinel-type structure of lithium manganese oxide. In its crystal structure, oxygen ions constitute a cubic close-packed framework, lithium ions occupy the tetrahedral interstitial sites (8a), and

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manganese ions are located in the octahedral interstitial sites (16d), collectively forming a three-dimensional channel for lithium ion diffusion.

Lithium manganate (LMO) with spinel structure has become a highly promising anode material for lithium-ion batteries due to its unique safety, cost-effectiveness and environmental benefits. The spinel structure of LMO provides inherent thermal stability, significantly reducing the risk of thermal runaway compared with layered oxide anodes such as $LiCoO_2$. Its sturdy frame prevents oxygen from being released at high temperatures, making it less prone to fire or explosion. This feature is crucial for applications that require strict safety standards, such as electric vehicles and portable electronic devices.

Manganese is the main component of LMO materials, with large reserves and low cost, priced at only one tenth of cobalt. This cost advantage directly reduces the production cost of batteries and promotes the large-scale commercial application of LMO. The spinel crystal structure possessed by LMO not only simplifies the synthesis process, but also further reduces manufacturing costs. Unlike cobalt based materials with heavy environmental burden, LMO does not contain toxic heavy metals such as mercury, and has better environmental compatibility. At the same time, its recyclability has been fully verified and it has mature manganese and lithium recovery processes. These characteristics make LMO perfectly aligned with global sustainable development goals, helping to reduce ecological footprint and support circular economy.

However, LMO also has obvious shortcomings. The three-dimensional lithium-ion channels in its spinel structure support fast charging and provide moderate energy density, making it suitable for hybrid vehicles and electric tools. But the high temperature performance of LMO is its main weakness: when the temperature exceeds 50 ° C, Mn^{3+}will dissolve and cause electrolyte oxidation, leading to rapid capacity decay of the battery. In addition, the Jahn Teller effect in the structure also limits its cycle life, with capacity retention typically dropping below 80% after 500 cycles. More seriously, the dissolved Mn^{2+}/Mn^{3+} ions will migrate to the cathode, forming an insulating layer and increasing the internal resistance of the battery [5].

Therefore, LMO is often used in scenarios that emphasize cost-effectiveness and moderate energy density, such as power tools and laptops in consumer electronics products. Its high magnification performance also makes it an ideal choice for electric two wheelers and hybrid vehicles. Meanwhile, the safety advantages and excellent low-temperature performance of LMO make it widely used in industrial backup power systems. In addition, in emerging fields such as grid energy storage and medical equipment, LMO is also a preferred solution when application scenarios prioritize stability and cost over ultimate energy density.

2.2. Lithium cobalt oxide

Lithium cobalt oxide ($LiCoO_2$) adopts an α - $NaFeO_2$ layered structure, and its crystal is hexagonal symmetric. In this structure, Li^+ and Co^+ ions occupy the 3a and 3b sites, respectively, both located in the oxygen octahedral interstices. The main framework is composed of CoO_6 octahedra connected by common edges to form a CoO_2 layer, which is very stable. The embedded LiO_6 octahedron shares edges with the CoO_2 layer, which helps to reduce the energy of the entire system.

In the O^{2-} lattice, Li^+ and Co^{3+} ions are arranged in an ordered manner, and due to their unique ionic radii, the material can form a regular two-dimensional layered structure at full charge. This structure provides a channel for efficient diffusion of Li^+ along the c-axis direction. In addition, the Co-O-Co orbital coupling effect present in CoO octahedra endows the material with high electronic conductivity.

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The theoretical capacity of lithium cobalt oxide is 274 mAh/g, and it can usually reach 150 mAh/g in practical applications. Its single cell operating voltage is as high as 3.7-4.2 V, significantly better than lithium iron phosphate and some ternary materials, which enables LCO based batteries to provide longer battery life at the same volume. The voltage platform during its charging and discharging process is very stable, especially suitable for scenarios such as mobile phones and laptops that require stable power output [6]. As the earliest commercialized lithium-ion cathode material, LCO's production process is mature and stable, suitable for large-scale manufacturing. Meanwhile, it has low internal resistance, good high current discharge performance, and supports fast charging [7].

Although lithium cobalt oxide (LCO) is widely used, it still faces significant drawbacks. This material is expensive and its resources are limited. As cobalt reserves in Congo account for 70% of the global total, this has pushed up the cost of batteries, and the supply chain remains vulnerable to geopolitical conflicts and mining regulations. Poor thermal stability causes safety issues; When the temperature is above 150°C or overcharged, LCO may experience structural collapse, release oxygen and pose an explosion risk. Therefore, an advanced battery management system (BMS) is required. Its cycle life is limited by irreversible oxygen oxidation and phase transition during deep cycling. Compared with alternatives such as LFP, its cycle life is restricted to approximately 2000 times. The environmental and health hazards are also prominent. Cobalt toxicity pollutes the ecosystem, and its high-temperature decomposition releases harmful Co^{3+} ions. In addition, technical limitations also include poor low-temperature performance, the risk of lithium plating at high temperatures, and an increased probability of dendrite short circuits caused by fast charging.

LCO is mainly used in high-energy-density lithium-ion batteries for consumer electronic products such as smart phones, laptops and tablets. Its compact size and stable voltage output make it an ideal choice for portable devices that require long battery life. Due to its fast charging capability, it also powers digital cameras, drones and wearable technologies.

Despite its limitations, LCO still dominates in small-scale applications where energy density and lightweight design are crucial. However, its application in electric vehicles and large-scale energy storage is limited by cost and safety issues.

2.3. Lithium iron phosphate

Lithium iron phosphate (chemical formula: LiFePO4) is a anode material with an olivine-like crystal structure, belonging to the ornate crystal system, and its space group is Pnma. In its crystal structure, oxygen atoms are arranged in a twisted hexagonal close-packed manner. Iron and lithium atoms respectively occupy the center of the octahedron, forming FeO6 and LiO6 octahedrons, while phosphorus atoms are located at the center of the tetrahedron, constituting the PO4 tetrahedron.

Lithium iron phosphate (LFP), as a typical olivine structural material, has excellent safety performance due to its strong P-O covalent bond providing a stable framework. The thermal decomposition temperature of this material is as high as 350℃, which is much higher than that of ternary materials. Moreover, the volume change during charging and discharging is only 6.8%, and its structural stability is outstanding. It is particularly suitable for long-life application scenarios such as energy storage power stations. In terms of cost, iron and phosphorus resources are abundant and non-toxic. The price of raw materials is only one-tenth of that of cobalt.

Lithium iron phosphate (LFP) materials are widely used in various energy storage systems due to their excellent stability, high safety, and long cycle life [8]. As a positive electrode material for high-power and long-life lithium-ion batteries, it is widely used in the field of electric vehicles, and effectively supports the grid connection and scheduling of renewable energy sources such as solar

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and wind energy in grid level energy storage scenarios. In addition, LFP also provides stable power for portable electronic devices that require high reliability power supply, such as power tools, uninterruptible power supplies (UPS), and medical equipment. Its excellent thermal stability and environmental adaptability also enable the material to meet the application requirements of harsh environments such as aerospace and marine engineering. In addition, the low cost and environmental friendliness of the material itself further enhance its practical value in sustainable energy solutions [9].

2.4. Ternary lithium

As an important branch of lithium-ion batteries, ternary batteries (NCM/NCA) use transition metal oxides of nickel, cobalt, manganese (or aluminum) as positive electrode materials. Its working principle is based on the reversible insertion and extraction of lithium ions between the positive and negative electrodes, which is mediated by the electrolyte and membrane.

Compared with lithium iron phosphate (LFP) batteries (150-220 Wh/kg), the core advantage of ternary batteries lies in their significantly improved energy density (200-300 Wh/kg). This feature can provide vehicles with longer range, for example, the Tesla Model S Plaid achieved a CLTC range of over 700 kilometers by using high nickel NCM batteries. In addition, ternary batteries can still maintain over 80% of their capacity in low temperature environments of -10 °C, with much lower low-temperature attenuation than LFP, making them more suitable for use in cold regions. At the same time, it supports fast charging at a 5C rate (which can be fully charged in 30 minutes), which is also better than the common 1C charging speed of LFP batteries. On the premise of achieving equal energy output, the volume and weight of ternary batteries are smaller, which helps optimize the spatial and weight layout of vehicles. In recent years, the evolution of high nickel (such as NCM811) and low cobalt technologies has continuously improved energy density while also reducing dependence on expensive cobalt materials, further enhancing their market competitiveness [10].

However, ternary batteries also face multiple challenges. Its safety performance is relatively weak, and the triggering temperature for thermal runaway is low (about 250-300 °C), which poses a high risk of thermal spread. The mechanical structure of batteries is susceptible to damage when subjected to impact, which may result in short circuits or electrolyte leakage. In terms of lifespan, ternary batteries typically only achieve 1000-2000 cycles, far lower than LFP batteries' over 3000 cycles, and their capacity deteriorates rapidly after long-term use. Its manufacturing cost is also high due to its high content of nickel and cobalt. Under high temperature conditions, the performance degradation and aging rate of ternary batteries will significantly accelerate. In addition, it is highly sensitive to overcharging and overdischarging and must be equipped with a sophisticated battery management system (BMS) for protection. Consistency control between individual cells is also a major technical challenge in large-scale grouping, which directly affects the performance and lifespan of the entire battery pack [11].

3. Prospects for cathode materials of lithium-ion batteries

The future of anode materials for lithium-ion batteries is driven by innovation, cost reduction and the constantly changing market demands. High-nickel ternary materials will enhance their energy density by optimizing the crystal structure and doping techniques. Solid electrolytes like sulfides will enhance safety and charging speed, while phosphate-based materials will expand in storage

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applications due to their cost advantage. Green manufacturing methods will meet stricter sustainability standards.

Cost pressure will drive the reduction of cobalt in ternary materials, and designs rich in nickel will become more common. Advances in nano-structures and artificial intelligence-driven production will enhance manufacturing consistency. From a regional perspective, China's dominant position in phosphate production contrasts sharply with the global efforts focused on the research and development of high-nickel variants for electric vehicles. By 2020, hybrid solutions combining different anode materials will dominate, and fast charging capability and extended cycle life will become key benchmarks. Supported by interdisciplinary innovation, the progress of this industry will balance energy density, safety and affordability.

4. Conclusion

Through research, it has been found that the current mainstream anode materials for lithium-ion batteries each have their own characteristics: $LiMn_2O_4$ (LMO) has cost advantages and safety features, but it faces the problems of poor high-temperature performance and short cycle life; $LiCoO_2$ (LCO) has a high energy density but is expensive and poses safety risks; $LiFePO_4$ (LFP) has become the preferred choice in the energy storage field due to its excellent safety and cycle stability; The ternary material stands out in terms of energy density and low-temperature performance, but its safety and cost restrict its development. Therefore, material selection should weigh performance indicators based on application scenarios. LFP is suitable for energy storage systems with high safety requirements, while ternary materials are more appropriate for the electric vehicle field that demands high energy density.

This paper systematically compares the performance characteristics of four types of anode materials. Its significance lies in: guiding industrial applications by providing material selection basis for battery manufacturers, clarifying research and development directions such as solving the manganese dissolution problem in LMO, reducing the cobalt content in ternary materials, and increasing the energy density of LFP, and promoting sustainable development by facilitating the development of low-cobalt/cobalt-free materials. Future research should focus on material modification such as the development of high-nickel ternary materials, process innovation such as the optimization of nanostructures, and system integration such as the design of hybrid anodes, while establishing a full life cycle assessment system to promote the development of lithium battery technology towards high safety, long life, and low cost.

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