Lithium Battery Technologies for Improvement of Energy Efficiency

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Abstract. With the process of economic globalization and the continuous improvement of energy demand, the search for new energy with higher efficiency has become a hot spot of social concern. Lithium-ion battery (LIB), as the current battery system with the best comprehensive performance, has the characteristics of high specific energy, high cycle life, small size and lightweight, and has rapidly developed into a new generation of energy storage power supply for information technology, new energy vehicles, aerospace and other fields of power support. Therefore, improving the energy efficiency of LIB is the most suitable choice in the current energy shortage. The core and key of LIB is the development and application of new lithium storage materials and electrolyte materials. This paper summarizes the research and application status of the main key materials of LIB. By analyzing the development status and existing problems of mainstream energy efficiency improvement technologies, it can be seen that the energy efficiency of LIB still has great room for improvement in the aspects of key materials and manufacturing technologies. At present, the research status of new anode materials and solid electrolytes is very active, and these technologies are expected to improve the energy efficiency, safety and reliability of lithium batteries. In the future, with more research and innovation, we can expect to see these technologies make even greater breakthroughs in the battery field, driving the development of electric mobility and renewable energy storage.

Keywords: Lithium-ion battery, Solid electrolyte, New negative electrode material.

1. Introduction

The rapid development of globalization has made our world increasingly digital and electrified. From smartphones to electric cars, wearables to home appliances, our reliance on electricity is increasing. This growth in dependence, combined with a growing global population, has led to explosive growth in energy demand. However, traditional energy resources such as oil, gas and coal are at risk of being depleted. Therefore, the search for renewable and efficient energy solutions has become a top priority [1].

Batteries play a crucial role in solving the problem of energy shortage. They cannot only store electricity, but also make renewable energy sources such as solar and wind more reliable and practical. Batteries also power electric vehicles, energy storage systems, mobile devices and countless other applications. Therefore, advances in battery technology are critical to achieving sustainable energy supply.

At present, there are many different types of batteries on the market, mainly lead-acid batteries, nickel-metal hydride batteries and lithium-ion battery (LIB). Each has unique characteristics and areas of application. With its advantages of high energy density, long life, lightweight and environmental protection, LIB has gradually become the mainstream of various batteries, and in the fields of electric vehicles, renewable energy storage and portable electronic devices, LIB's wide application is promoting the energy revolution and providing strong support for solving the problem of energy shortage. However, LIB still suffers from problems such as limited capacity and energy density, long charging time, and limited lifetime. At present, the main solution is to improve the energy efficiency of LIB, and its mainstream methods include the study of new electrode materials and the use of solid electrolytes. This paper will mainly analyze the impact of new anode materials and solid electrolyte on LIB and compare their respective advantages and disadvantages, so as to develop an efficient LIB with higher energy density and higher safety in an innovative way [2].

2. Basic principle of LIB

LIB is mainly composed of positive and negative electrode materials that can undergo reversible de-incarceration reactions, electrolytes that can transport lithium ions, and membranes (Fig. 1) [3]. The positive and negative electrodes with a certain chemical potential difference achieve reversible energy release and storage through controlled REDOX reaction. The essence of the electrochemical process contained in it can be considered to be the transformation of REDOX that occurs simultaneously at a chemical site in a chemical reaction into effective separation in physical space through different charge transport carriers, such as the use of electronically insulated lithium-ion conductor electrolyte to achieve internal positively charged lithium-ion transport, and negatively charged electrons through external wires to achieve current flow. That is, electrons flow through the outer loop and lithium ions flow through the inner loop. People now widely used LIB follow the basic architecture of traditional electrochemical batteries, the core working parts of the battery mainly includes positive electrode, negative electrode, electrolyte and diaphragm 4 parts, in addition to other non-core support parts, such as fluid collection, adhesives, conductive additives, battery lead pole and packaging materials. It differs from other electrochemical cells in that it uses lithium ions as the energy transport medium and the electrode is embedded in the electrochemical lithium storage mechanism [4].

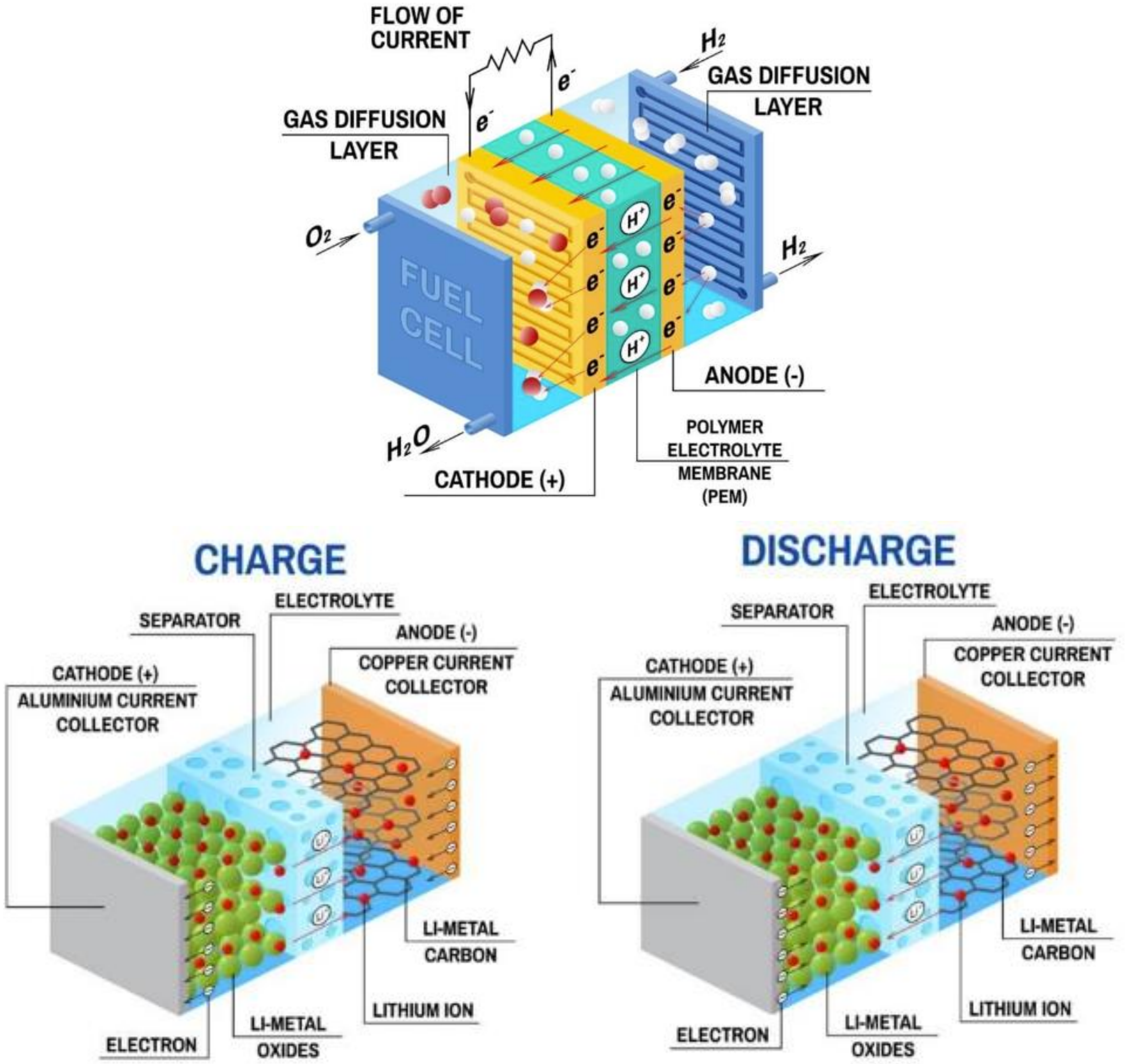

Figure 1. Operating principle of lithium battery [5]

3. New anode materials and designs

The low capacity of lithium-ion battery electrode material is related to the poor performance of charging and discharging at high current, so the key to improve the performance of lithium-ion battery is to find a kind of negative electrode material with high theoretical capacity and high-rate performance [6]. The chapter mainly discusses several main methods for the application of new negative electrode materials, including the application of multi-functional materials composite materials, cationic substitution technology and nanostructure design. Each of them has its characteristics and advantages, which can significantly improve the energy efficiency of LIB.

3.1. Multifunctional composite materials

Among many negative electrode materials, the theoretical capacity of transition metal carbonate is 1600 mA h Reaching g-1, it has excellent advantages such as convenience of large-scale production, ease of synthesis process and low cost, making it an ideal commercial graphite alternative material. However, there are obvious defects in transition metal carbonate, such as instinctive reduced conductivity and structural degradation, which prevent further development. Therefore, there is no doubt that increasing the electrical conductivity and structural stability of electrons/ions will be the basis for improving the electrochemical properties of transition metal carbonate. Transition metal carbides have attracted considerable attention for improving lithium storage performance by combining them with other components such as carbon-based materials, metallic compounds, and conductive polymers to form multiphase composites. Carbonaceous materials with ultrafine electron mobility, high carrier mobility and excellent mechanical flexibility are widely used as conductive additives and structural stabilizers for transition metal carbon [7].

3.2. Cationic substitution

In LIB, cationic substitution technology is an important research area aimed at improving battery performance, safety and cycle life. This technique involves partially or completely replacing one or more cations (usually manganese, iron, nickel, copper, etc.) in a lithium-ion battery with other metal ions to improve the battery's performance. Cationic substitution shows excellent properties in improving the conductivity of transition metal compounds. A major trend in cationic substitution technology is to replace some or all of the nickel ions of lithium nickel oxide (LiNiO2) with other metal ions such as cobalt, iron or manganese. High-nickel cathode materials have high capacity and high voltage, which can provide higher energy density, but also come with thermal runaway and cycle life problems. With suitable cation substitution, the researchers are trying to ameliorate these problems to achieve safer and longer-lasting lithium batteries [4]. When ions with larger radius are doped into the crystal structure, the original cell will expand, resulting in increased surface spacing and wider ion transport path. Second, the doped element partially replaces the host element or enters the interval, increasing the conductivity through the overlap of electron orbitals and charge distortion between adjacent atoms. In general, doped elements can be divided into metallic elements and non-metallic elements, and for transition metal compounds, metal cations are more easily replaced, and the impact is more obvious.

3.3. Nanometer structure design

A multi-stage structure consisting of nano-level building blocks can improve the electrochemical performance of a material. The micrometer-level structure can suppress particle accumulation, thus maintaining a stable electrode structure and active site. Secondly, nanoscale components can maintain the superior structural properties of nanomaterials, such as abundant electrochemical active sites, shorter lithium-ion diffusion paths, and faster reaction kinetics [7]. The hollow structure of the LIB anode has wide applicability to improve the ability to release strain and cope with volume expansion. This hollow structure has excellent electrochemical performance due to its high specific surface area, low density, and short charge transfer path. In addition, the hollow structure promotes sufficient penetration of the electrolyte, increases the active specific surface area, and reduces the charge/ion transfer distance. More importantly, the hollow structure with sufficient space between the FeCO3 and the body effectively responds to large volume changes.

4. Application of inorganic solid electrolytes

The all-solid electrolyte can be classified into inorganic solid electrolyte (ISE) and polymer solid electrolyte (PSE) according to its composition. Compared with PSE, ISE has the advantages of better thermal stability, higher ionic conductivity, lower activation energy and higher lithium-ion mobility, so it has received wide attention.

4.1. Lithium ion conduction mechanism of ISE

For all-solid electrolytes, the conduction of lithium ions occurs to a large extent through defects. Defects include line defects, point defects, body defects and surface defects, and point defects have the greatest influence on ion conduction. Typical point defects include Schottky defects and Frenkel defects, where a cation and an anion are displaced from the corresponding lattice position to the crystal surface, thus forming both cationic and anion defects in the body. A Frenkel defect occurs when an ion is transferred from its lattice position to a void, resulting in a vacancy.

In ISE, the conduction mechanism of lithium ion mainly includes vacancy mechanism, gap mechanism and exchange mechanism. The vacancy mechanism is usually based on the Schottky defect, which creates a large number of vacancies in the crystal that can be used for ion jumping, and after one lithium-ion jumps, a new vacancy is created in the original location, allowing the lithium ion to transport and follow the cycle. For the interstitial mechanism, interstitial lithium ions are continuously diffused in the interstitial space between the molecular skeleton by continuously displacing lithium ions at adjacent available sites.

In order to achieve the rapid ion conduction of ISE, the electrolyte needs to meet the following conditions: (1) a suitable conduction channel for moving lithium ions to pass through; (2) A continuous diffusion path constructed by interconnecting vacancy and gap sites, and these adjacent sites should have low ion migration barrier energies; (3) Because lithium ions will affect each other during the conduction process and interact with the surrounding environment, thus affecting the ionic conductivity, it is necessary for lithium ions to have a weak interaction force with the main skeleton. However, most of the existing ISE do not meet the ionic conductivity requirements of all-solid-state LIB, which has become a major obstacle limiting its application. Therefore, various attempts have been made to improve the ionic conductivity of solid electrolytes, and some progress has been made.

4.2. The development status of ISE

Recent developments in the field of ISE include the study of new inorganic solid electrolyte materials. Researchers are developing solid electrolyte materials with high ionic conductivity and superior mechanical stability, such as sulfides, oxides, and borates. And in order to overcome the interface problem between solid electrolyte and electrode, researchers focus on interface engineering research to improve battery performance and stability. This includes innovations in coating, interface treatment and electrode design. And constantly improve the manufacturing process, because preparing high-quality, uniform and dense solid electrolytes is a challenge. The researchers are looking for cost-effective preparation methods to mass-produce high-performance ISE. However, the current development of ISE still has many shortcomings, and the preparation cost of some inorganic solid electrolyte materials is high, which may limit the feasibility of commercialization. In addition, the interface between the electrode and the electrolyte remains a challenge and can cause performance degradation.

5. Comparison between new anode materials and inorganic solid electrolytes

New anode materials and inorganic solid electrolytes (ISE) are both important technologies used to improve the efficiency of LIB, and each has some advantages and disadvantages, which are compared in Table 1.

Table 1. Comparison between new anode materials and inorganic solid electrolytes [8, 9]

Types	Principle	Advantage	Disadvantage
New negative electrode material	Further improve the performance of LIB by improving their energy density, cycle life, power density and safety.	High energy density, long battery cycle life, high efficiency of the battery.	High preparation cost, difficult engineering
Inorganic Solid Electrolyte (ISE)	Inorganic solid electrolyte can significantly improve the performance of LIB by improving ionic conductivity, thermal stability and cycle stability.	More safety, high temperature resistance, long battery cycle life.	Difficult manufacturing, high cost, low conductivity, low material stability.

The new electrode materials and ISE have their own advantages and challenges in improving the efficiency of LIB. In practice, the choice of technology depends on the demand and cost consideration of the specific application. Some applications may be better suited to the use of novel electrode materials, while others may benefit from the high safety and stability of ISE technology. Therefore, in the field of LIB, the appropriate technology is usually selected according to the specific needs, or a combination of the two is explored to achieve better performance [10].

6. Conclusion

LIB play an important role in the new energy automobile industry, while traditional commercial LIB is difficult to meet the growth requirements of various new industries, high energy density, high safety, and high energy The new, high-energy-density, high-safety LIB are considered the focus of the development of the next generation of LIB. It is the key to the development of high-performance batteries that improve the performance of electrode materials and the focus of scientific research in the field of batteries. The electrolyte is the core of LIB and plays an important role in the performance of LIB.

The new anode material has a higher lithium-ion storage capacity, which improves the energy efficiency of LiBs by increasing the energy density of batteries and having high-capacity characteristics. Solid electrolytes eliminate the risk of leakage and expansion of liquid electrolytes and can operate over a wider temperature range, increasing the reliability of the battery. In addition to this, solid electrolytes are able to transport ions faster, increasing the power density of the battery, allowing it to charge and discharge faster.

These two mainstream methods have different advantages and disadvantages, and their future can further improve the energy efficiency of lithium batteries through complementary advantages, including material innovation, interface engineering, preparation process optimization and multifunctional battery design, to further improve the performance of lithium-ion batteries to meet the needs of different application fields. These technologies will continue to play a key role in energy storage and mobile power.

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