Development Status and Prospects of Lithium-ion Power Batteries for Electric Vehicles

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***Abstract*—Major countries and automobile manufacturers in the world jointly promote the transformation of automobile energy and boost the development of electric vehicles. As the most widely used power battery, the lithium-ion power battery comes under the spotlight. The progress of lithium iron phosphate batteries and ternary lithium batteries has given rise to the hope of transformation. And the breakthrough of solid-state batteries has laid a solid foundation for future high-performance batteries. This paper reviews and analyzes the strengths and weaknesses of three power batteries, and evaluates their modifications, application, and current situation. It can be concluded that ternary lithium batteries cannot replace lithium iron phosphate batteries and solid-state batteries temporarily cannot be widely produced and applied.**

***Index Terms*—Electric vehicles, ternary lithium battery, lithium iron phosphate battery, solid-state battery, blade battery.**

I. Introduction

With the depletion of resources and the deterioration of the earth's environment, fuel vehicles that produce exhaust greenhouse gas and noise pollution have caused people's anxiety and dissatisfaction. Therefore, electric vehicles are one of the core strategies to break the shackles of energy and the environment with higher efficiency.

As the core component which plays a decisive factor in the performance of electric vehicles, efficient, safe, and low-cost power battery is the never-ending goal of global vehicle companies and battery manufacturers. Hence, the technological development of widely employed lithium-ion batteries with enormous potential will be closely related to the success of future electric vehicles [1]. Lithium-ion batteries make up for the shortcomings of lead-acid batteries and have become the mainstream of power batteries for electric vehicles. Nevertheless, its flaws such as the appalling safety and the short service life delay the pace of the rapid development of electric vehicles. Aiming at the difficulties and the requirements of lithium-ion battery technology, the comprehensive review begins with an overview of lithium-ion batteries and then demonstrates their operating principles and characteristics of main lithium-ion power batteries. Finally, it explores the current situation and forecasts of lithium-ion power batteries.

II. Overview of Lithium-ion Batteries

In the 1970s, M. Stanley Whittingham and John B. Goodenough made remarkable progress by reversibly disembedding lithium ions from the cathode. Later, Akira Yoshino and Sony Corporation invented the first commercial rechargeable lithium-ion battery in 1991.

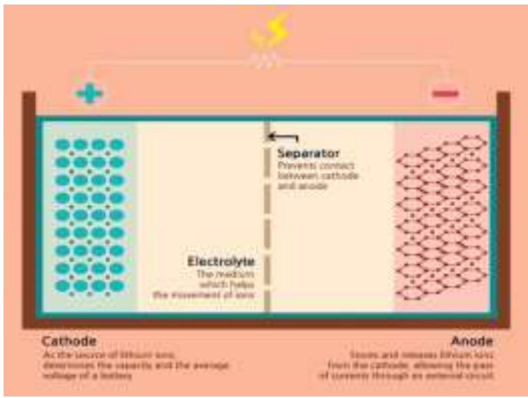

Fig. 1. The four components of Li-ion Battery [2].

The four major functional components of a lithium-ion battery are cathode, anode, electrolyte, and separator (shown in Figure1). Lithium-ion batteries rely on the movement of lithium ions between the cathode and the anode to operate. When the battery is charging, lithium ions will be released by the cathode and then be received by the anode through the electrolyte and the separator, generating a flow of electrons in the same direction to the lithium ions around the external circuit. These lithium ions are finally embedded in the micropores of the layered anode. Similarly, when the battery is discharging, the lithium-ion embedded in the anode carbon layer will move back across the electrolyte and generate energy for the power battery. The process of discharge of a Li-ion Battery is shown in Fig. 2.

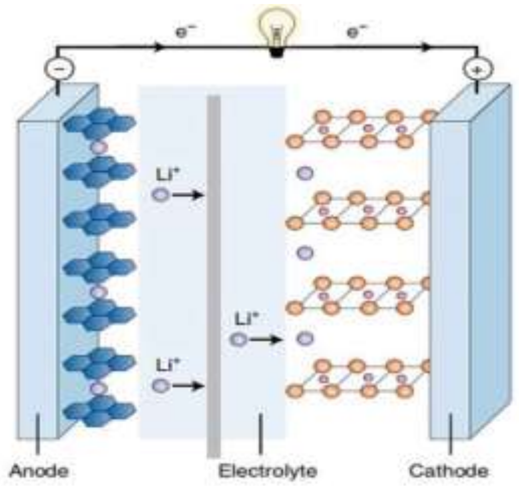

Fig. 2. Discharge of a Li-ion battery[3].

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The power batteries used in electro automobiles include the lead-acid battery, the nickel-metal hydride battery, and the lithium-ion battery. Owing to higher energy density and lightweight without memory effect, the lithium-ion battery stands out among other batteries. It is clear from Table I that lithium-ion batteries show absolute advantages of greater energy density, longer cycle life, lower self-discharge and higher cell voltage among lead-acid batteries and nickel-metal hydride batteries. With the continuous development and expansion of the electric vehicle industry, lithium iron phosphate batteries and ternary lithium batteries have been unable to meet people's complex demands for power batteries. Recently, BYD from China focuses on the blade battery based on the lithium iron phosphate battery, and Toyota from Japan and Dyson from the United Kingdom also start further research on solid-state battery technology.

TABLE I: THE COMPARISON OF PERFORMANCE INDICATORS OF THREE MAIN POWER BATTERIES FOR ELECTRIC VEHICLES [4]

Battery Type	Gravimetric Energy Density (Wh/kg)	Cycle Life	Self-discharge/ Month	Cell Voltage
Lead-acid Battery	30-50	300-500	30%	2V
Nickel-metal Hydride Battery	60-120	500-100	20%	1.25V
Lithium-ion Battery	110-160	> 1000	2%	3.6V

III. MAIN LITHIUM-ION POWER BATTERIES

A. *Lithium Iron Phosphate Battery*

The lithium iron phosphate battery adopts lithium iron phosphate($LiFePO_4$) as the anode and graphite or carbon electrode as the cathode. Firstly, the lithium iron phosphate battery is low-cost. As the anode material, $LiFePO_4$ depends on the carbothermic or high-temperature solid-state reaction to synthesize in industry. Those methods with simple operation ensure large-scale production of $LiFePO_4$ and abundant raw materials (Li, Fe, P) also mean lower synthetic costs, compared with the lack and high cost of cobalt and nickel in ternary materials. Secondly, the lithium iron phosphate battery has great safety performance and excellent thermal stability. The thermal decomposition temperature of $LiFePO_4$ is around 700 ℃, while those of ternary materials are from 200℃ to 300℃. And the P-O bond in $LiFePO_4$ is extremely strong and stable. The Lewis structure of $LiFePO_4$ is shown above in the Fig. 3.

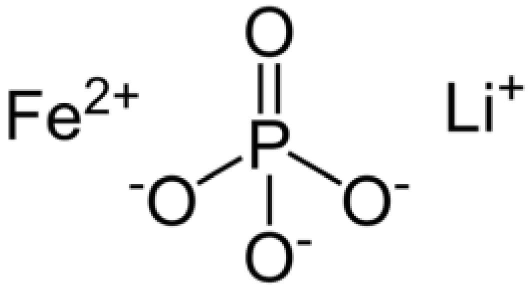

Fig. 3. The Lewis structure of $LiFePO_4$ [5].

Therefore, its structure in Fig. 3 will not break down and collapse even though the lithium iron phosphate battery works at high temperatures for a long time or overcharges many times. Besides, there is no risk of combustion and explosion like traditional lithium-ion batteries when the battery is damaged or short-circuited. [6] Thirdly, the lithium iron phosphate battery has a long cycle life and low self-discharge which greatly save the cost of purchasing and repairing batteries. It can work more than 2000 times under standard charging (0.2C, 5 hours) for 10 years. The comparison of cycle life and self-discharge between the three main power batteries for electric vehicles is shown above in Table I. Meanwhile, the lithium iron phosphate battery has some performance drawbacks. The orthorhombic olivine structure of $LiFePO_4$ is shown in Fig. 4.

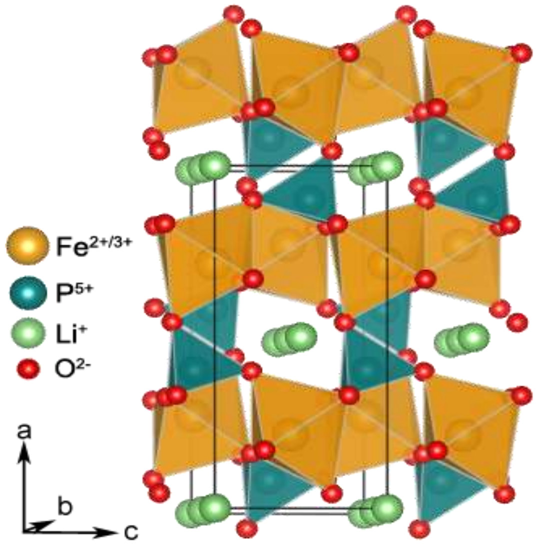

Fig. 4. The Crystal Structure of $LiFePO_4$ [7].

The structure of $LiFePO_4$ poses the insurmountable obstacles in reaching its theoretical capacity, resulting in low tap density, low intrinsic electronic conductivity, and low ion diffusion rate of Li^+. [1] The peculiar structural of $LiFePO_4$ indicates low energy density and poor low-temperature performance, which restricts the application in private cars. The test conducted by the Army Engineering University of PLA proves that as the temperature decrease, the internal resistances of charge migration and electrode polarization increase. [8] This inverse relationship reveals that the lithium iron phosphate battery cannot support vehicles to run as usual at low temperatures. Thus, some automobile companies choose to abandon lithium iron phosphate batteries as power batteries and turn to ternary lithium batteries or solid-state batteries. The performance indicators of the certain lithium iron phosphate battery are shown below in Table II.

TABLE II: THE PERFORMANCE INDICATORS OF THE CERTAIN LITHIUM IRON PHOSPHATE BATTERY

Performance Indicators	Gravimetric Energy Density (Wh/kg)	Cycle Life	Cell Voltage(V)
Lithium Iron Phosphate Battery	130	2000	3.2

B. *Solid-State Battery*

The main difference between the batteries (shown in Fig.

5) is that lithium-ion batteries employ a liquid electrolytic solution, whereas solid-state batteries adopt a solid electrolyte.

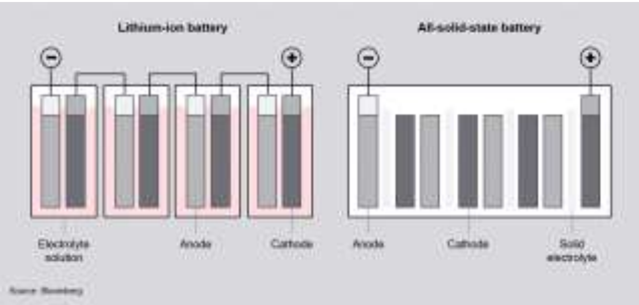

Fig. 5. The structures of Li-ion battery (left) and solid-state battery (right) [12].

An electrolyte is an electrically conducting chemical that produces electric current as a result of a dissociation into anions and cations. Solid-state lithium batteries include solid-liquid lithium batteries and all-solid-state lithium batteries. Solid-state lithium batteries and traditional lithium-ion batteries have no difference in the working principle. The medium of lithium-ion migration changes from liquid to solid which has a higher energy density and a more stable structure. The solid electrolyte is considered as the core for the change of the battery technology because it can gather more charged ions at one end and then increase the energy density.

The solid-state power battery has the potential to solve two key problems for electric vehicles – energy density and safety. The solid-state battery has no requirement for a diaphragm and liquid electrolyte, which account for nearly 40% of the volume and 25% of the mass of the power battery. Hence, the selection of a solid electrolyte can simplify the battery package and cooling system and save space for more cells in battery modules, improving the energy density. [7] In 2020, Toyota announced that the solid-state battery theoretically made a leap of a trip of 500 km on one charge and recharge from zero to full only in 10 minutes. Furthermore, the removal of flammable liquid electrolytes directly avoids the corrosion and volatilization of the liquid, the intensified reaction and the generation of oxygen at high temperatures, and the combustion caused by the leakage of the liquid. The solid-state battery also provides a more stable structure to inhibit dendrite growth and increase cycle life. According to the current research and development progress, there are still technical problems for the solid-state battery to overcome. The contact area between solid electrolytes and electrode materials is smaller than that of a ternary lithium battery, lowering the transmission speed of ions and ionic conductivity. [7] So far, scientists have not found suitable solid substances for the electrolyte: the polymer has insufficient temperature resistance and low ionic conductivity; the inorganic oxide has low ionic conductivity; the sulfide has a low transmission speed of ions.

IV. Lithium-ion Power Battery Development Status and Prospect

A. *Lithium Iron Phosphate Battery*

The installation capacity of lithium iron phosphate batteries in 2020 was 24.4 GWh, accounting for 38.6% of the electric vehicle market. Although electric vehicles with lithium iron phosphate batteries have a small market share in recent years, the volume of sales has increased by nearly 20% compared to 2019. Thanks to excellent safety performance, long lifespan, and low raw material cost, lithium iron phosphate batteries have been researched and developed by major battery manufacturers and automobile companies. Although its low energy density and low intrinsic conductivity limit its application in electric vehicles, some electric vehicles with special purposes have no needs to develop towards high energy density. For instance, the safety and reliability are more significant for city buses or delivery vehicles without battery volume requirements to carry cargos and passengers on routes. [5] In addition, the affordability and price rationality prompt car purchasers to choose electric vehicles with lithium iron phosphate batteries when the cost of ternary lithium batteries remains tremendously high. [5] Consequently, lithium iron phosphate batteries still occupy an irreplaceable position in the public bus, delivery vehicles, and special vehicles.

To achieve effective improvements to the low energy density of the lithium iron phosphate battery, BYD launched the blade battery that has thinner and longer cells like the blade. The blade battery substantially improves volume utilization by eliminating some components from cell to pack and significantly increases the energy density from 130 Wh/kg to 180 Wh/kg. [8] Moreover, the blade battery keeps the heat exchange efficiency at a high level and maintains the stability of the battery in a low-temperature environment.

Lithium iron phosphate batteries will not be replaced by ternary lithium batteries in future research and development. More innovative technologies and breakthroughs similar to blade batteries will emerge to continuously upgrade battery performance. The research has found that carbon coating, reduction of particle size, and doping with cations supervalent of Li^+ can compensate for material disadvantages.

B. *Ternary Lithium Battery*

The installation capacity of ternary lithium batteries in 2020 was 38.9 GWh, accounting for 61.4% of the electric vehicle market. At present, ternary lithium batteries overturn the erroneous understanding of electric vehicles and are widely used in private automobiles and passenger vehicles. The speedy development and the rising market share of ternary lithium batteries in recent years benefit from its high energy density. [9] In 2013, Tesla became the electric vehicle giant for the utilization of NCA as the anode material of power batteries, which has elevated the battery range to new heights and relieved the concerns. [1] In China, many automakers such as BYD and BAIC have also employed ternary lithium battery technology to replace lithium iron phosphate batteries originally used in electric vehicles. With the greater demand for power batteries, high-nickel ternary lithium batteries have sparked heated debates in the power battery industry. As the Ni content of the ternary lithium battery increases, the capacity of the ternary lithium material and the energy density of the battery will improve. [10] The existence of high-nickel ternary lithium batteries cannot address the inferior performance of safety and cycle life. [11] The spontaneous combustion caused by the ternary lithium battery has brought huge damage to property and casualties, raising the question about the safety of ternary lithium batteries. [6] To solve the above problems, ion doping, surface coating, and functionally graded materials have been further researched for the modification of ternary material modification. [10]. There is a definite development trend that the ternary lithium battery becomes the mainstream technology in the power battery market.

C. Solid-State Battery

Solid-state batteries with great potential are in the research and development stage. At present, the electric vehicle industry undoubtedly pays the most attention to the development of solid-state batteries. Brands such as BMW, Toyota, Dyson, Volkswagen, and many new car manufacturers have invested heavily in the solid-state battery. In 2021, NIO launched the company's fourth electric model ET7 equipped with a solid-state battery that will have a battery range of up to 1,000 kilometers. Obviously, solid-state batteries may be one of the directions of power battery technology in the future and have a long challenging way to achieve industrialization. Even if the solid-state battery is mass-produced in a short time, it will not show absolute advantages over the lithium iron phosphate battery or the ternary lithium battery. The immature technology and expensive vacuum equipment make the manufacturing cost of solid-state batteries high and unaffordable. The current technical route of solid-state batteries is to firstly develop solid-liquid lithium batteries, gradually reduce the content of liquid electrolytes, and finally realize all-solid-state lithium batteries. [11]

V. Conclusion

This paper combines the performance and the status of batteries to predict the future development trend. The lithium-ion battery with unique performance advantages is one of the main power batteries for electric vehicles. Lithium iron phosphate batteries are widely used in logistics and public transportation, while ternary lithium batteries are extensively adopted in private cars. The modifications of low-temperature performance and low energy density of lithium iron phosphate batteries have increased its market share and enlarged the applicable area. Ternary lithium batteries have a broader application prospect in the electric vehicle industry for research of thermal runaway performance and high-nickel ternary materials. New technologies like blade batteries and solid-state batteries ensure that the lithium-ion battery industry develops in a progressing and sustainable direction. Solid-state batteries still have key technical difficulties to resolve, but they have shown the potential to be market leaders. In summary, an affordable power battery with high safety and high energy density must be designed and produced in the future.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

This paper is independently completed by the author.

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