Status and Development of Cathode Materials for Lithium-Ion Batteries

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Abstract. Driven by the energy transition and the wave of electrification, efficient battery technology is a core requirement in today's society. Lithium-ion batteries, with their high energy density and long lifespan, occupy an important place in sustainable energy storage solutions. However, the overall performance and economics of the batteries greatly depend on the cathode materials used in them, and innovations in this area are critical to the advancement of battery technology. This study focuses on the latest research findings on cathode materials for lithium-ion batteries, providing an in-depth analysis of key materials such as lithium cobalt oxide, lithium manganese oxide, lithium nickel oxide, lithium iron phosphate, and ternary materials. The article details the chemical properties and performance optimisation of these materials. Through a comparative analysis, this paper aims to reveal the comprehensive performance of different cathode materials and explore their potential for improving battery energy density, reducing cost, and enhancing safety. The importance of this research lies in the fact that it provides an in-depth understanding of cathode materials for lithium-ion batteries, offering a key guide to the innovation and development of future battery technologies. This is not only of practical significance for the advancement of efficient, economical, and environmentally friendly battery technologies but also provides a valuable reference for related industries and academia.

Keywords: lithium-ion batteries, cathode materials, ternary cathode materials.

1. Introduction

With the growing global demand for renewable energy and efficient energy storage systems, lithium-ion batteries have become a ubiquitous energy storage solution due to their excellent energy density, long cycle life, and high voltage platform. Since their commercialisation in 1991, Li-ion batteries have been widely used in portable electronic devices, electric vehicles, and large-scale grid storage systems, making them one of the core technologies driving the development of modern mobile electronic devices and electric vehicles [1].

Despite significant advances in LIB technology over the past few decades, existing technologies face increasing challenges as the global demand for higher energy density, safer, and more environmentally friendly batteries continues to grow. Improvements in battery performance depend heavily on the chemical and structural properties of the materials within them, particularly the cathode materials. The properties of cathode materials directly affect the energy output, stability, cost, and safety of batteries, so the development of new high-performance cathode material has become a hot topic in the field of battery research.

This paper focuses on the research progress of anode materials for LIB, aiming to sort out and summarise the latest development of current major cathode materials. The current research on lithium cobalt oxide electrode materials has been relatively mature. Lithium cobalt oxide has good electrochemical performance and an operating voltage of 3.6 V, which will remain the mainstream product in the market in the short term [2]. Materials such as lithium manganese and lithium iron phosphate have attracted a great deal of research interest due to their low cost and good thermal stability, even though they have a relatively low energy density. Lithium nickel oxide has become a popular choice in the EV industry due to its high energy density, but the issues of its safety and cycle life still need to be addressed. Meanwhile, ternary materials, containing nickel, cobalt, and manganese,

have shown significant advantages in terms of overall performance and are at the forefront of cathode material research.

After analysing the properties and applications of these materials, this paper will also explore the importance of the development of cathode materials for achieving higher performance, more environmentally friendly, and economical lithium-ion batteries, as well as the challenges and future development directions. The research in this paper is expected to provide valuable references and insights for the future research of cathode materials for LIB.

2. Introduction to LIB

2.1. LIB composition

LIB are mainly composed of a positive electrode, a negative electrode, electrolyte and diaphragm. At present, the widely used positive electrode materials include lithium- iron, nickel, cobalt, manganese and other metal oxides. The negative electrode materials include graphite, silicon-carbon and so on. The electrolyte is an organic solvent of lithium hexafluorophosphate; the diaphragm is a polypropylene/polyethylene/polypropylene (PP/PE/PP) polymer membrane.

2.2. Basic principles of LIB

LIB is a general term for batteries with lithium-ion embedded compounds as the cathode material. The charging and discharging process of LIB is the intercalation and de-intercalation process of lithium ion. In the process of charging and discharging, lithium ions in the positive and negative electrodes transfer back and forth between the two electrodes, so the LIB is also called "rocking chair battery".

As soon as the battery is charged, lithium ions are produced at the positive electrode and go to the negative electrode via the electrolyte. Because carbon's negative electrode is layered, it contains a large amount of microporous material. The carbon layer's micropores receive the intercalation of lithium ions that make it to the negative electrode. The higher the charging capacity, the more intercalated lithium ions there are. Similar to this, the lithium ions intercalated in the carbon layer of the negative electrode become dislodged and migrate back to the positive electrode when the battery is depleted, or used. The discharge capacity increases with the amount of lithium ions that return to the positive electrode.

Taking the lithium battery with C as the cathode material and lithium manganese oxide as the cathode material as an example, the specific reaction is presented as follows.

(-)Cn|electrolyte|$LiMO_x$(+)

$$\text{Cathode reaction:} \quad LiMO_x \rightleftharpoons Li_{1-y}MO_y + yLi^+ + ye^- \tag{1}$$

$$\text{Anode reaction:} \quad C_n + yLi^+ + ye^- \leftrightharpoons Li_yC_n \tag{2}$$

$$\text{Total reaction:} \quad LiMO_x + C_n \leftrightharpoons Li_{1-y}MO_y + Li_yC_n \tag{3}$$

2.3. Advantages of LIB

1) The operating voltage is large, as can be seen in Table 1, which is three times that of NiMH and Ni-MH batteries; this is also an important reason for its high energy density.
2) High energy density, according to the unit volume or unit mass of the energy stored in the calculation of large, so the lithium-ion battery storage of the same electric energy volume is small, lightweight, that is, can be miniaturised.
3) Long cycling life.
4) Small self-discharge, 1/3 to 1/4 of NiMH and NiCd batteries.
5) Large battery capacity, twice as much as the equivalent cadmium-nickel batteries, better adapted to wartime communication for a long time.

6) No memory effect, the memory effect is the battery is not finished with electricity, re-charge when the charge drops, and nickel-metal hydride batteries, especially nickel-cadmium batteries, the memory effect is heavier [3].

Table 1. Comparison of the performance of LIB with nickel-hydrogen and Cadmium-nickel batteries [4].

	Lithium ion battery	Nickel-hydrogen battery	Cadmium-nickel battery
Operating voltage (V)	3.6	1.2	1.2
Specific energy by weight (Wh/kg)	100-140	65	50
Volume specific energy (Wh/L)	270	200	150
Charge/discharge life (times)	500-1000	300-700	300-600
Self-discharge rate (%/month)	6-9	30-50	25-30
battery capacity	high	middle	low
memory effect	\	slight	serious

3. Cathode materials

The cathode materials in LIB account for more than 40% of the cost of the whole battery, and under the current technical conditions, the energy density of the overall battery mainly depends on the cathode materials. Hence, the cathode materials are the core materials for the development and research of lithium-ion batteries. The cathode materials for the mature applications at present include LCO ($LiCoO_2$), lithium manganese dioxide ($LiMn_2O_4$), lithium iron phosphate ($LiFePO_4$), and lithium nickel cobalt manganese oxide ($LiNiCoMnO_4$). Among them, $LiCoO_2$, $LiFePO_4$, and $LiNiCoMnO_4$ are the materials with larger usage in the current market. The improvement of cathode materials for Li-ion batteries during the last few decades and the direction of technology going forward are briefly summarized here.

3.1. Lithium cobalt oxide

$LiCoO_2$ is one of the most widely used and earliest researched materials in cathode materials for LIB. $LiCoO_2$ can be obtained in two different structures at different production temperatures, which are the layered structure and the spinel structure. The de-embedding of lithium ions during the charging and discharging of LIB is impeded by the spinel structure, which makes the electrochemical performance fail to meet the application requirements, and therefore has not been put into actual production [5]. The layered structure of $LiCoO_2$ is more conducive to the transport of lithium ions, so the electrochemical performance is also the best and is widely used.

At present, the method of preparing $LiCoO_2$ is mainly solid-phase synthesis, which can be divided into high-temperature solid-phase synthesis and low-temperature solid-phase synthesis according to different reaction temperatures. The more commonly used method is the high-temperature solid-phase synthesis method, which uses $LiCoO_2$ or LiOH lithium salts and $CoCO_3$ cobalt salts in accordance with the molar ratio of Li:Co=1:1, and then calcined at 600-900 ℃ under air atmosphere [6].

The benefits of $LiCoO_2$ include a higher working voltage, consistent charge and discharge power, high particular energy, strong cycling performance, and suitability for a high-current charge as well as discharge, high conductivity, and a simple production process. However, the study of lithium cobalt oxide material found that its operating voltage must be within 4.25 V, otherwise, the performance of lithium batteries will decline rapidly. At this time, lithium cobalt oxide material will undergo an irreversible phase transition process, where the Li ions in the lithium cobalt oxide charge/discharge cycling process of de-embedding behaviour has been limited to reduce the capacity of the battery at the same time, reduce the service life of lithium batteries [7]. Therefore, in order to

improve the performance of $LiCoO_2$, researchers have modified it using methods such as doping and capping.

By using a solid phase technique, Bang et al. manufactured Ni-doped $LiNi_{1-y}Co_yO_2$ material, which they discovered to have a first discharge capacity of 147.6 mAh/g at y=0.5 and an energy decay rate of just 1.4 mAh/g/cycle [8]. In theory, aluminum atoms have a maintaining effect on the layered structure of LCO, which can inhibit the irreversible phase transition of its structure under high working conditions. Jaephil Cho et al.applied aluminum trioxide coating to LCO, and ultimately, a material with a propensity for particular discharge as high as 174 mAh/g at a working voltage between 2.75 V and 4.4 V has been prepared, and the cycle life has been significantly improved [9].

3.2. Lithium nickel oxide

Researchers have also studied lithium nickel oxide relatively early, and the most commonly used lithium-nickel cathode material is $LiNiO_2$. Its synthesis method is mainly to mix LiOH and $Ni(OH)_2$ in accordance with the ratio of nickel to lithium molar ratio of 1/1.1 to 1/1.5, and then react in an oxygen atmosphere at 600-750 el to lithium molar ratio of 1/1.1 to 1/1.5,thium-nickel cathode

$LiCoO_2$ has a low self-discharge rate, no pollution, good compatibility with various electrolytes, and is comparatively economical than $LiCoO_2$. However, its preparation conditions are harsh, its stability is poor, and it is easy to change its structure during charging and discharging, which makes the battery's cycling performance deteriorate and its capacity decay fast.

To address the above problems, Wang Ziyun et al. prepared $LiNi_{1-x}Zr_xO_2$ (x = 0, 0.01, 0.03, 0.05) cathode materials with different doping contents using sol-gel method with zirconium nitrate as zirconium source. The results showed that the capacity of $LiNi_{1-x}Zr_xO_2$ (x = 0.01, 0.03, 0.05) was superior to that of $LiNiO_2$ at all multiplicities, and the $LiNi_{0.97}Zr_{0.03}O_2$ electrode material possessed a discharge capacity of 67.7 mAh/g, which was much higher than that of $LiNiO_2$ cathode material (39.82 mAh/g), while the cycling performance of the Meanwhile, the cycling performance of $LiNi_{0.99}Zr_{0.01}O_2$ cathode material is 74% at 100 mAh/g energy density for 50 cycles, and the Cycling ability declines as Zr doping content rises, and the undoped retention rate is 57.3%. It is evident that the multiplicity and cycle stability of $LiNiO_2$ cathode materials can be enhanced by the right amount of Zr doping [11].

3.3. Lithium manganese oxide

Among the lithium-ion cathode materials with the greatest development potential is lithium manganese oxide, and the most commonly used lithium manganese cathode material is $LiMn_2O_4$, whose crystal structure is spinel structure.

$LiMn_2O_4$ preparation methods mainly include solid-phase technique, microwave technique, sol-gel technique, and hydrothermal technique. Considering the simple process and easy operation of the solid phase synthesis method, it is currently used as the main method for the synthesis of $LiMn_2O_4$. In this method, Li_2CO_3 and MnO_2, which are mixed by sufficient grinding, are sintered and held at 380-840 it isr 1 day, and then the target product can be obtained by removing it after it is reduced to room temperature. However, the finished products obtained by this method are difficult to control the particle size and particle size fractionation, which affects their electrochemical properties. Some researchers have effectively solved this problem by using the microwave-assisted rheological phase method and template method [12].

The advantages of $LiMn_2O_4$ lie in the abundant resources of Mn metal, low cost, low pollution, high safety, non-toxicity, and good overcharge resistance. However, its theoretical capacity is not high, its structure is very unstable, and it has a John-Teller effect [13]. The material is prone to lattice distortion during the deep charging and deep discharging, which causes the battery capacity to rapidly degrade, in particular when operating at higher temperatures, the attenuation is aggravated. So how to control the decay of $LiMn_2O_4$ at high temperatures becomes a major issue. Now the modification methods of lithium-site doping, manganese-site doping, and oxygen-site doping are introduced.

The doping of lithium-sites is the doping element partially replacing the Li position in the $LiMn_2O_4$ structure. Na+ is usually used to replace part of Li+, and since Na+ is less electrochemically active than

Li+, Na+ can stay in the three-dimensional channels of Li+ diffusion during the charging and discharging process, which plays the role of supporting the Li+ diffusion channels. Xiong et al. successfully prepared a series of Na+ doped $LiMn_2O_4$ materials $Li_{1-x}Na_xMn_2O_4$ (x = 0, 0.005, 0.01, 0.02, 0.04, 0.06), and the experimental data showed that the Na+ doped samples did not change the spinel structure of $LiMn_2O_4$, but the cycling properties of the material were significantly improved, and the elevated ion diffusion coefficient was associated with the enhancement of the electrochemical characteristics [14].

Mn-site doping, on the other hand, involves metal cations (M=Ni, Fe, Zn, Mg, Al, Ti, etc.) replacing the Mn position in $LiMn_2O_4$, and the metal cations partially substituting for equal amounts of Mn^{3+} and Mn^{4+}. Yi et al. successfully prepared Co-doped $LiMn_2O_4$ anode material $LiMn_{1.95}Co_{0.05}O_4$ by rheological phase reaction method, using LiOH-H_2O, MnO_2, and Co_3O_4 as the lithium, manganese, and cobalt dopant sources. $LiMn_2O_4$ anode material $LiMn_{1.95}Co_{0.05}O_4$. Electrochemical performance tests showed that the first discharge specific capacity of Co-doped $LiMn_2O_4$ was 112.5 mAh/g, the first Coulombic efficiency was 88.4%, and the specific capacity was maintained at 100 mAh/g after 100 cycles, with a capacity retention rate of 88.9%. However, the specific capacity of the Co-undoped $LiMn_2O_4$ cathode material decays from 111.2 mA h/g to 87.9 mA h/g with a capacity retention of 79%, which shows a significant improvement in its performance [15].

Oxygen doping is the replacement of the O position in $LiMn_2O_4$ by dopant elements such as S, Cl, F, etc. F replaces O to enhance the bonding energy and thus improve the stability of the crystal structure, while Cl and S replace O to increase the lattice constant and facilitate the diffusion of lithium ions. Bakierska et al. successfully synthesised $LiMn_2O_4$ and $LiMn_2O_{3.99}S_{0.01}$ by sol-gel method, using S as the doping source and CH_3COOLi $2H_2O$, $(CH_3COO)_2Mn$-$4H_2O$, $(NH_4)_2S$ and NH_3-H_2O as the raw materials. $4H_2O$, $(NH_4)_2S$ and NH_3-H_2O as raw materials, $LiMn_2O_4$ and $LiMn_2O_{3.99}S_{0.01}$ anode materials were successfully synthesised by the sol-gel method. By comparison, the specific capacity of the $LiMn_2O_4$ material was 112 mAh/g for the first discharge, which decayed below 100 mAh/g after the 10th turn, whereas the specific capacity of the $LiMn_2O_{3.99}S_{0.01}$ material was 112 mAh/g. $LiMn_2O_{3.99}S_{0.01}$ material has a first discharge specific capacity of 183 mAh/g, which is 125 % of the theoretical specific capacity of the $LiMn_2O_4$ material, with almost no capacity decay after 15 cycles [16].

3.4. Lithium iron phosphate

In the field of studying cathode materials for lithium-ion batteries, lithium iron phosphate is an explosive subject, of which the most representative material is $LiFePO_4$ with an olivine-type crystal structure. The common methods of preparation are high-temperature solid-phase method, carbothermal reduction, liquid-phase synthesis method, and so on.

$LiFePO_4$ has a wide range of raw material sources, and has the advantages of high stability, high security, high energy, long life, green and non-polluting, etc., and is thought to be the potentially best cathode material for lithium-ion batteries by researchers, but $LiFePO_4$ has low electronic and ionic conductivity, low vibrational solid density, and the synthesis process of Fe^{2+} is highly susceptible to oxidation into Fe^{3+}, while requiring relatively pure inert atmosphere protection, and due to the lithium ions in the de-embedding process of $LiFePO_4$/$FePO_4$ phase, which will lead to lattice distortion, and then affect the conductivity and ion diffusion rate, so that the specific capacity of $LiFePO_4$ cannot be effectively played.

Currently, the multidoping of LFPs has become a popular research topic. Compared with single doping, multiple co-doping is more conducive to the improvement of electrochemical performance. Gao et al. synthesised pure $LiFePO_4$ and $Li_{0.99}Zr_{0.0025}Fe_{1-x}Co_xPO_4$ (x = 0.005, 0.01, 0.015, 0.02) cathode materials by the traditional solid phase approach at high temperatures. Electrochemical performance experiments demonstrate that the doped samples outperform the pure $LiFePO_4$ in terms of electrochemical performance, while structural and morphological studies indicate that Zr and Co co-doping can enhance the structural stability and change the particle morphology of $LiFePO_4$. The greatest electrochemical performance is demonstrated by $Li_{0.99}Zr_{0.0025}Fe_{1-x}Co_xPO_4$, which, at 0.1 C, has a starting battery capacity of 139.9 mAh/g and, after 50 cycles, retains 85% of its capacity [17]. It is apparent that Zr and Co co-doping could significantly improve LiFePO4's electrochemical performance.

3.5. Ternary material

Ternary cathode materials for LIB integrate the advantages of a single component and have more excellent performance than mono-component cathode materials, which is a promising cathode material. Among them, nickel-cobalt-manganese ternary anode material $LiNi_{1-x-y}Co_xMn_yO_2$ is the focus of current research. According to the research, it is found that different ratios of nickel-cobalt-manganese do not lead to structural changes, but the performance is quite different. It can be roughly divided into two categories: nickel-manganese equivalent (e.g. $LiNi_{0.33}Co_{0.33}Mn_{0.33}O_2$) and nickel-rich (e.g. $LiNi_{0.5}Co_{0.2}Mn_{0.3}O_2$), the former during the procedure of charging and discharging the +4-valent Mn invariant valence, play a stabilising role of the structure, charging process of the Ni^{2+} will be oxidised into Ni^{4+}, for the active element, can improve the capacity; the latter In the process of charging and discharging, +3-valent Co and +2/+3-valent Ni are oxidised, and Mn has no change in valence, which plays a role in stabilising the structure. When the charging voltage is lower than 4.4 V, Ni is mainly involved in the electrochemical reaction, forming Ni^{4+}; Co is involved in the reaction at higher voltage, forming Co^{4+}. Therefore, the higher the Ni content, the greater the reversible specific capacity of the material for charging and discharging below 4.4 V. The Co content significantly affects the specific capacity of the ions. The content of Co significantly affects the ionic conductivity, the higher the content of Co, the better the conductivity and the better the charge/discharge multiplication [18].

Ternary material preparation can be accomplished in a variety of approaches, mainly using co-precipitation, hydrothermal and solvothermal synthesis method, sol-gel method, and other methods, to prepare the precursor, and then through the ordinary high-temperature calcination, microwave method, and other high-temperature solid-phase reaction to synthesise the final product.

Modification of ternary materials can further improve their performance so that they have better stability, higher energy density, and so on. At present, the most studied doping of ternary system cathode materials is cation doping and anion doping.

Doping the cations of equivalent valence state will not change the valence of the atoms in the original material, and can stabilise the structure of the material, expand the ion channels, and improve the ionic conductivity of the material. Wilcox et al. prepared a ternary material $LiNi_{1/3}Co_{1/3-y}M_yMn_{1/3}O_2$ doped with Fe, Al, and Ti, respectively (M=Fe, Al, Ti). It was shown that the multiplicity performance, cycle stability, and voltage of the material doped with a small amount of Al was improved, is with the increase of doping A content of discharge capacity instead of decreasing; doped with a small amount of Fe also makes the discharge capacity slightly decreased; doped with a small amount of Ti on the material's potential for discharge is not much effect [19].

More research is being conducted on anion doping, which substitutes F, Cl, and S for some of the O in the material, which is more electronegative. The material's ability is increased while also improving its stability and crystallinity. This is because the chemical bond involving F and the transition metal ions has a larger bonding energy, which creates a tighter binding [20]. Kim et al. studied F and Mg-doped $LiNi_{1/3}Co_{1/3-y}M_yMn_{1/3}O_2$ and analysed that according to the experimental results the doping of Mg resulted in the improvement of the capacity and cycling performance of the ternary material and reduced cation mixing, on the other hand, the cycling performance of the ternary material co-doped with F and Mg was more stable [21].

4. Conclusion

This paper introduces several main cathode materials for lithium-ion batteries. From the earliest lithium cobalt oxide to the new ternary cathode materials now, each material has its unique advantages and limitations. The development history of cathode materials for LIB reflects the progress of science and technology and changes in market demand. Currently, although many high-performance cathode materials are available, many challenges remain, such as increasing capacity, improving safety, reducing costs, and addressing supply chain issues. Future research should focus more on integrating multidisciplinary knowledge, such as chemistry, materials science, engineering, and economics, to

develop more sustainable and cost-effective cathode materials. At the same time, in order to achieve long-term sustainability of lithium-ion batteries, researchers also need to find alternative materials, optimise the production process and consider the recycling and reuse of batteries. In short, the research and development of cathode materials is an ongoing process that will continue to drive the advancement of LIB technology and the expansion of application areas.

References

[1] WANG Chongguo, LIU Guanglong, JIN Xiaorong, HOU Wendong. Research progress of anode materials for lithium-ion batteries[J]. Contemporary Chemical Research,2023,(09):12-14.

[2] Lu Xiaoting. Research progress of cathode materials for high-capacity lithium-ion batteries[J]. Synthetic Materials Aging and Application,2022,51(04):121-123.

[3] Bo Shengmin. Lithium-ion batteries and their materials[J]. Inorganic Salt Industry,2002(05):19-20.

[4] Chen Hongchao, Li Xiangdong. Research status and application prospect of lithium-ion battery principle[J]. Military Communication Technology,2001,22(01):55-58.

[5] QIN C, JIANG Y, YAN P, et al. Revealing the minor Li-ion blocking effect of LiCoO2 surface phase transition layer[J]. Journal of Power Sources,2020,460: 228126.

[6] Yin R Z, Kim Y S, Shin S J. In Situ XRD Investigation and thermal properties of mg doped LiCoO2 for lithium ion batteries[J]. Electrochemical Society. 2012,159(3):A253-A258.

[7] NADKARNI N, ZHOU TNADKARNI, FRAGGEDAKIS D, et al. Modelling the phase coexistence in LixCoO2 for energy and information storage[J].Advanced Functional Materials,2019,29(40):1616-3028.

[8] Bang E Y, Mumm D R, Park H R, et al. Lithium nickel cobalt oxides synthesized from Li2CO3, NiO and Co3O4by the solid-state reaction method[J]. Ceramics International,2012,38:3635-3641.

[9] CHO J, KIM Y J, PARK B. Novel LiCoO2 cathode material with Al2O3 coating for a Li ion cell[J]. Chemistry of Materials, 2000,12(12):3788-3791.

[10] LIU Wanmin, QIN Mulan, DENG Jiyong et al. Progress in the storage performance of nickel-rich LiNiO2-based cathode materials[J]. Functional Materials,2018,49(12):12023-12031.

[11] Wang Ziyun. Research on doping modification of lithium nickel oxide lithium-ion battery cathode materials[D]. Chang'an University,2020.

[12] WANG Ling, GAO Pengzhao, LI Dongyun, HUANG Shiting, XIAO Hanning. Research progress of cathode materials for lithium-ion batteries[J]. Silicate Bulletin,2013,32(01):77-84.

[13] Liu R S, Shen C H. Structural and electrochemical study of cobalt doped LiMn2O4 spinels[J]. Solid State Ionics, 2003,157(1-4):95-100.

[14] Xiong L L. The electrochemical performance of sodium-ion modified spinel LiMn2O4 used for lithium-ion batteries[J]. Journal of Solid State Electrochemistry,2014,18(3):713-719.

[15] Yi X, Wang X, Ju B, et al. Elevated temperature cyclic performance of LiAlxMn2-xO4, microspheres synthesized via co-precipitation route[J]. Journal of Alloys & Compounds 2014,604(16):50-56.

[16] Bakierska M. Nature of the electrochemical properties of Sulphur substituted LiMn2O4 spinel cathode material studied by electrochemical impedance spectroscopy[J]. Materials,2016,9:696-707.

[17] Libin Gao, Zhengrui Xu, Shu Zhang. The co-doping effects of Zrand Co on structure and electrochemical properties of LiFePO4 cathode materials[J]. Journal of Alloys and Compounds,2018,739:529-535.

[18] ZHAO Hang, WEI Gang, KANG Xin, LI Suping. Research progress of ternary cathode materials for lithium-ion batteries[J]. China Ceramics,2020,56(05):10-15.

[19] WILCOX J, PATOUX S, DOEFF M. Structure and electrochemistry of LiNi1/3Co1/3-yMyMn1/3O2(M=Ti,Al,Fe)positive electrode materials[J]. Journal of the Electrochemistry Society,2009,156(3): A192-A198.

[20] WU Zhe, HU Shuwan, CAO Feng, et al. Research progress of lithium nickel cobalt manganese oxide ternary cathode materials[J]. Power Supply Technology,2018,42(07):1079-1081.

[21] KIM G H, MYUNG S T, BANG H J. Synthesis and electrochemical properties of Li[Ni1/3Co1/3Mn(1/3-x)Mgx]O2-yFy via coprecipitation[J]. Electrochemical and Solid State Letters,2004,7(12): A477-A480.