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Investigating advanced strategies for enhancing energy density in Lithium-Ion batteries

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Abstract. Lithium-Ion batteries have become a versatile energy storage solution for various applications, such as portable electronics and electric vehicles, due to their numerous advantages. The increasing demand for higher energy density has prompted researchers to explore innovative strategies to improve the performance of these batteries. This study systematically investigates cutting-edge techniques aimed at enhancing the energy density of lithium-ion batteries. By conducting a detailed analysis of different battery components, this study evaluates the feasibility, efficiency, and potential impact of these approaches on future battery technologies. By giving some concrete examples, such as NMA($LiNi_{1-x-y}Mn_xAl_yO_2$), LFP($LiFePO_4$) batteries in cathode, popular silicon-based materials in anode, novel dual conductive binder and solid electrolyte (solid electrolyte interface), some of the working principles are described and the electrochemical properties of the batteries are comparatively analysed. This research aims to provide readers with a comprehensive understanding and research direction for advancing the energy density capabilities of lithium-ion batteries.

Keywords: Lithium-Ion Batteries, Energy Density, NMA, LFP, Silicon-Based Anodes, Electrolytes.

1. Introduction

As the global environment continues to deteriorate and fossil fuels continue to be depleted, there is an increasing global demand for clean and sustainable energy. Electric energy storage systems, particularly those based on clean energy sources like wind and solar power, have become a focal point in the world's energy agenda. Developing efficient and high-capacity storage systems has become a significant global challenge. Electrochemical batteries are renowned for their exceptional efficiency, reliability, and flexibility, making them prominent within the field of electric energy storage systems. Specifically, lithium-ion batteries have emerged as the most prominent choice due to their numerous advantages, including low cost, high-energy density, and long cycle times. The profound significance of lithium-ion batteries in electric vehicles, portable electronics, and related industries is widely acknowledged. However, a major obstacle remains in the quest to increase the energy density of lithium-ion batteries in order to minimize weight and augment capacity.

Enhancing the energy density of Li-ion batteries can be achieved through various approaches. These include improving positive and negative electrode materials, electrolytes, diaphragms, collectors for the inactive part, as well as enhancing the interfacial structure in the batteries and exploring novel battery polarization mechanisms. Some studies focus on highly using electron-ion hybrid conducting active materials for the positive electrode, realizing all-solid-state electrodes with all-active materials, and optimizing electrode materials or increasing the proportion of active materials in the battery to improve energy density. Similarly, since the lower limit of energy density of lithium-ion batteries depends on the cathode material, new cathode materials are explored, such as lithium iron phosphate batteries, and ternary polymer lithium batteries have good energy density and practical applications. In terms of electrolyte, the more promising methods are mixing RTIL with appropriate amount of traditional carbonate solvents and co-solvents, modifying the solid electrolyte SEI film by adding additives or changing the electrolyte substance, and so on. In addition, the inactive structure "collector" in innovative batteries, micron-sized silicon-based materials for anode materials, silicon-graphite composites, and silicon-wire anodes all have great influence. Similarly, the lower limit of energy density of Li-ion batteries depends on the cathode material. Therefore, researchers have been exploring new cathode materials, such as lithium iron phosphate ($LiFePO_4$) and ternary polymer ($Li\text{-}PO_3$) batteries, which have shown good energy densities and practical applications. In terms of electrolyte, there are several promising methods being investigated. These include mixing RTIL with appropriate amounts of traditional carbonate solvents and co-solvents, modifying the solid electrolyte SEI film by adding additives or changing the electrolyte substance, and more. Additionally, innovations in the inactive structure of the battery, such as the use of polymer composite materials and nanomaterials in the diaphragm, have also made a significant impact.

However, even with the multitude of studies aimed at improving the energy density of lithium-ion batteries, there are still numerous unanswered research questions that need to be addressed. One particular challenge is the energy density of traditional cathode materials for lithium-ion batteries, which has almost reached its theoretical limits. This makes it difficult to achieve significant advancements without the invention of novel materials and electrode designs. In the past few years, there has been a growing focus on investigating the positive electrode of lithium-ion batteries than the negative electrode. While there have been advancements in materials such as micron-sized silicon-based materials, silicon-graphite composites, and silicon-wire anodes for the anode, the research on the negative electrode has not progressed as much. This paper will describe in detail some of the cutting-edge methods to increase energy density, replacing NMC cobalt ions with aluminium ions, various additions of highly conductive materials to LFPs, anode materials containing silicon, and various electrolytes. Comparing their electrochemical properties to demonstrate their high energy density and future potential in the power battery market.

2. Advancing methods in cathodes

In the present-day, it is unfathomable to envision a society that does not rely on lithium-ion batteries, which compose its foundation. These batteries, commonly recognized by the positive electrode $LiCoO_2$ and the negative electrode graphite, continue to dominate the portable electronics market due to their exceptional qualities such as high compression density, remarkable energy density, unwavering cycle life, and reliable performance. Analogous to $LiCoO_2$, several advanced materials with distinct advantages have emerged, including $LiFePO_4$ electrodes acknowledged for their enhanced safety and $LiMn_2O_4$ electrodes celebrated for their prolonged cycle life. The pivotal influence of the battery emanates from its positive electrode, which directly determines its energy density, safety, and cycle life. Consequently, the positive electrode material profoundly affects various factors that dictate energy density, such as specific capacitance, voltage platform, ionic electron conductivity, and structural stability. In their relentless pursuit of enhancing battery performance, scholars relentlessly concentrate their efforts on achieving a breakthrough in one of these areas during the battery research and development process.

2.1. NMA

In addition to lithium iron phosphate (LFP) and lithium manganese oxide (LMO) mentioned in the previous section, there are two types of Ni containing lithium batteries high-nickel $LiNi_{1-x-y}Mn_xCo_yO_2$ (NMC) and $LiNi_{1-x-y}Co_xAl_yO_2$ (NCA) have also taken a share of the market with their excellent energy density. However, since cobalt metal is a scarce and expensive metal, the thermal stability of cobalt-containing electrodes is not so good when subjected to heat, and NMC and NCA materials are susceptible to thermal runaway and safety accidents at high temperatures, overcharging, and overdischarging. A cobalt-free nickel-containing electrode material $LiNi_{1-x-y}Mn_xAl_yO_2$ (high-nickel NMA) then stands out. By virtue of its enhanced voltage and comparable rate capability, this particular candidate demonstrates potential for serving as the next generation of cobalt-free lithium-ion batteries that are high-energy. Additionally, it is both adjustable and scalable, further enhancing its viability.

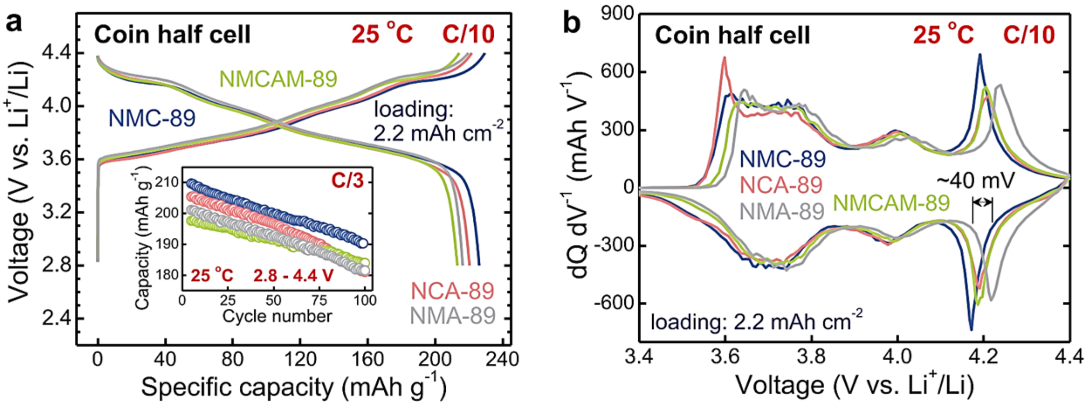

Figure 1. Specific capacity and average voltage of NMA-89, NCA-89, NMC-89, and NMCAM-89 [1].

The above roughly mentioned some influencing factors of energy density, one of the important points is the voltage plateau, here to add that the voltage plateau refers to the stable voltage interval of electrode materials in the process of charging and discharging, and usually higher voltage plateau means higher average voltage, and vice versa is also closely related. The energy density (Wh/kg) is obtained by multiplying the specific capacity (mAh/g) and the average voltage (V).

Li et al. conducted a study on four different cathode materials for lithium-ion batteries, specifically NMC-89, NCA-89, NMCAM-89, and NMA-89, to determine their specific capacities at a voltage range of 2.8-4.4 V using a C/10 charging rate [1]. The variations in specific capacities among these materials can be attributed to the difference of all kinds of characteristics of each metal ion. Although the specific capacity of NMA is slightly lower compared to the other materials, its difference is not significant. However, Figure 1 reveals that the average voltage of NMA is approximately 40 mV higher than that of NMC, suggesting that NMA can achieve a comparable capacity density even without cobalt metal, thereby reducing the overall cost.

Despite the cost and energy density advantages of NMA, its cycle performance remains a challenge. After 100 cycles, The NMA-Li half battery already had a noticeable drop in capacity retention [2]. Additionally, the NMA full cell (LTO) electrode utilizing $Li_4Ti_5O_{12}$ as the anode exhibits an initial discharge capacity of 186 mAh/g and a capacity retention rate of 81% after 200 cycles. With such a low-capacity retention rate, it is difficult to have some application value in the current stage of battery development and use. Recent advancements have addressed these issues by coating a stable protective layer, such as oxides (e.g., Al_2O_3, ZrO_2), carbon, and conductive polymers, on the surface of NMA materials. These coatings effectively inhibit undesirable reactions on the surface, and ion doping with elements like Mg, Ca, etc., can enhance the lattice structure of NMA.

It is important to note that while the cycling performance of NMA may be subpar, there will not be a significant degradation in the morphology and crystal structure of NMA. The exceptional structural stability of NMA will minimize capacity decay, thereby contributing to the energy density. Therefore, overall, NMA will emerge as the dominant cathode material for the next generation of lithium batteries due to its superior energy density and affordability.

2.2. LFP

The emergence and development of ternary lithium batteries such as NMC, NMA, nickel-rich lithium batteries made of ternary layered oxides, largely stems from the pursuit of high-capacity batteries and the continuous pursuit of improving battery energy density. They all have a tendency to become the new mainstream. However, in the mainstream of the lithium iron phosphate (LFP), with its strong safety, stability, is still a kind of battery we are not difficult to give up, there are still a lot of scientific research in this direction.

Its strong safety can be attributed to its olivine-like structure, which supports the lithium iron phosphate material during the embedding and extraction of lithium ions. This structure minimizes volume changes, preventing internal floor collapse or physical deformation of the electrode. Additionally, $LiFePO_4$ material exhibits high thermal stability, with a decomposition temperature around 750°C, much higher than that of ternary material (200-300°C) [3]. It also does not experience oxygen precipitation during decomposition [3], which effectively limits the occurrence of thermal runaway reactions, such as oxidation or reduction of the electrode material, that could lead to explosions. However, it should be noted that the olivine-like structure of lithium iron phosphate material hinders the movement rate of lithium ions, resulting in reduced ion transport rate and a relatively low energy density. In the pursuit of enhancing the energy density of lithium iron phosphate batteries, extensive research has been conducted on hybrid electrodes to optimize their properties. One such method involves exploring the potential of lithium manganese iron phosphate ($LiMn_yFe_{1-y}PO_4$) as an improved version of lithium iron phosphate lithium-ion batteries. Researchers have experimented with different anions, such as PF_6^-, in mixed graphite electrodes. Another approach includes utilizing a hybrid electrode composed of lithium and manganese-rich transition metal layered oxides (LMR-NMC) along with LFP. Moreover, efforts have been made to enhance the structural properties of electrodes by incorporating carbon-coated lithium-iron phosphate composite cathode materials with carbon layers. Several cutting-edge examples of improved batteries are provided below.

The enhancement of energy density has been hampered by the ionic conductivity of LFPs. However, hybrid electrodes present a solution for this issue. In particular, the LFP/graphite-20% electrode offers a wider voltage range and high capacity, which is especially beneficial in a full-cell configuration. The research conducted by Hao et al. provides insight into the charging and discharging process of the hybrid LFP/graphite-20% positive electrode LFP battery [4]. At lower voltages, lithium ions are removed from the LFP phase reversibly, while at higher voltages, they are reversibly inserted into the graphite phase. This sequential insertion and removal process distinguish it from conventional lithium-ion and dual graphite batteries.

The inclusion of graphite greatly enhances the electrical conductivity of lithium ions, promoting the process of lithium ion embedding and removing at relatively lower voltages. Consequently, When the voltage environment is between 2.5V and 4V, lithium ions move out of the LFP layer of material, leading to an augmented discharge capacity of the battery. When the voltage environment becomes higher, up to 5 V, the graphite phase can accommodate reversible intercalation of PF_6^- ions from the electrolyte. Despite the limited proportion of graphite, the hybrid electrode also facilitates the release of PF_6^- ions, thereby further augmenting the cell's charging capacity. This, in conjunction with the improved electrical conductivity of lithium ions by graphite, contributes to the heightened energy density. This mechanism diverges from the constraints of the 'rocking chair' mechanism, allowing for a broader voltage range for the staged decalcification/intercalation mechanism of Li^+ cations and PF_6^- anions. It overcomes the limitation of a narrower voltage window.

The number of cycles has not decreased but has, in fact, increased, and the overall performance of the battery has considerably improved in both half-cells and full cells. Some researchers may be interested in increasing the graphite proportion to further expand the voltage window and enhance energy density. However, it is important to consider that a sole enhancement may not be ideal, as an excess of graphite can hinder the formation and performance of the cathode/electrolyte interphase (CEI) layer, thereby affecting safety performance and cycle life.

It is evident that incorporating graphite, a highly conductive material, in the positive electrode material offers significant benefits. Additionally, doping graphite in the positive electrode material, similar to lithium- and manganese-rich transition-metal layered-oxide (LMR-NMC) or excessive metal layered oxides, can compensate for the relatively low energy density of LFP.

In order to improve the conductivity of electrodes, it is feasible to generate additional conductive substances, such as carbon materials, through the self-reaction of the materials used for the electrodes. Recently, there has been an increasing usage of biomass materials in the production of cathodes and anodes for lithium-ion batteries. The presence of internal carbon in these biomass materials typically impacts the eventual composition and structure of the electrodes.

Zhao et al. effectively produced a composite of carbon-encapsulated lithium iron phosphate (GC/IC/LFP) with carbon flakes inside by employing a process involving hydrothermal-alcoholic washing and calcination [5]. This composite material utilizes phytic acid as the phosphorus source and glucose as the carbon source. Comparatively, the lithium iron phosphate cathode materials containing internal carbon flakes exhibit superior electrochemical performance in terms of specific capacity, stability, and capacity recovery when compared to regular lithium iron phosphate cathode materials. Consequently, these cathode materials hold significant application value and prospects.

Glucose plays a crucial role in the GC and IC synthesis process. During the hydrothermal-alcoholic washing-calcination process, glucose decomposes at high temperatures, generating carbon encapsulation and internal carbon flakes. By incorporating highly efficient conductive materials, it enhances electron transmission, charging/discharging rate, and energy efficiency of the battery. Another innovative aspect of this battery is the utilization of phytic acid. Firstly, phytic acid is a biomass material, aligning with the concept of green chemistry and manufacturing of new energy vehicles and green products. It is rich in phosphorus and forms an ordered self-assembly structure with other precursors during the synthesis process. This ordered self-assembly facilitates the formation of uniform lithium iron phosphate crystals in the subsequent calcination process [5]. The diffusion and migration of lithium ions inside the crystals can be improved, leading to a slower capacity degradation of the battery during long-term use and enhanced battery performance. This successful production resulted in a higher energy density than that of conventional LFP, which demonstrates the positive interaction between graphene flakes and lithium ions. The redox reaction between graphene flakes and lithium ions assists in the transportation of lithium ions. Hence, it is reasonable to propose that the high energy density of the GC/IC/LFP material is also influenced by a similar reaction. However, further comprehensive experiments are necessary to reach a definitive conclusion.

3. Advancing methods of anodes

When it comes to traditional negative electrodes, graphite electrodes have been predominantly used. The focus of improving energy density in traditional graphite electrodes lies in material modification and structure optimization. For instance, the spacing between layers can be adjusted, the arrangement of the material lattice can be altered, and the electrode porosity can be optimized to enhance the transport rate of lithium ions. Material modification aims to improve conductivity, similar to the positive electrode. One approach is to add carbon black to the negative electrode, which forms a conductive network and reduces internal resistance, thereby improving conductivity. Nanomaterials are considered, and binders like polyvinylidene fluoride are included to enhance structural stability. Material properties can also be improved through oxidation, doping, and even enhancing the hydrophilicity of graphite materials. The limits of conventional anode materials are being fully exploited in various aspects.

In addition to these optimization methods, the development of composite materials is also a major focus in traditional lithium-ion battery anodes. The emergence and advancement of silicon composite materials have significantly contributed to the development of current anode materials, making it the most important direction of development at this stage. The rapid progress of silicon-based anodes is attributed to their extremely high theoretical specific capacity, reaching 4200 mAh/g, which is much higher than that of graphite anodes. This is because silicon-based anodes can form $Li_{15}Si_4$ with embedded lithium during the process, allowing each silicon-based anode to accommodate approximately 4.4 lithium atoms, a significantly higher capacity compared to graphite anodes that can accommodate only one.

Since the 1990s, the use of silicon anode materials has presented challenges in terms of volume expansion and contraction. This remains a significant issue in scientific research, particularly when used in composite materials. Additionally, low cycle counts have been a problem. However, there are cutting-edge silicon anode batteries that address these challenges. Silicon-graphite (Si-Gr) anodes experience volume changes during repeated recharging of lithium-ion batteries with electricity. This occurs because the silicon absorbs lithium ions, forming a lithium-silicon compound (Li-xSi), which leads to volume expansion. During discharge, the lithium ions detach from the Li-xSi compound, causing volume shrinkage. This repeated expansion and contraction can result in wear and tear of the silicon particles, reducing their effective volume and lowering energy density and capacity. In addition, these broken particles can also cause damage to various parts of the battery. For example, they can rupture the SEI membrane, which is a type of solid electrolyte that will be discussed in a subsequent article. This rupture can lead to the growth of more lithium dendrites and result in detachment or damage to the active material. Ultimately, this will reduce the overall cycle life of lithium-ion batteries.

3.1. Pre-lithiation

Pre-lithiation can partially inhibit the volume change of the composite negative electrode. It involves embedding lithium ions in silicon before battery assembly, reducing the subsequent expansion and shrinkage of the silicon particles during charging and discharging. Without pre-lithiation, the battery tends to embed lithium ions in graphite during charging, leading to non-uniform lithium-ion transport between graphite and silicon and increasing local stress, which exacerbates volume change. On the other hand, pre-lithiation promotes more homogeneous transport, thereby mitigating these issues. In summary, the pre-lithiation process can be seen as a trade-off, sacrificing a small loss of capacity in the initial cycles for a longer cycle life.

Kim's team proposed a pre-lithiation technique that involves evaporating lithium onto a silicon-graphite anode containing silicon particles with a diameter of 100 nm [6]. This method addresses some of the aforementioned concerns by offering a convenient process without requiring battery disassembly or leaving behind inactive material. Furthermore, it enables precise control over lithium deposition. Pre-lithiated negative electrodes in fully charged batteries exhibit extended cycle life and increased area capacity, as shown in Figure 2. Put simply, this technique compensates for the depletion of lithium ions during the initial charging and discharging cycles by replenishing them through the deposited lithium.

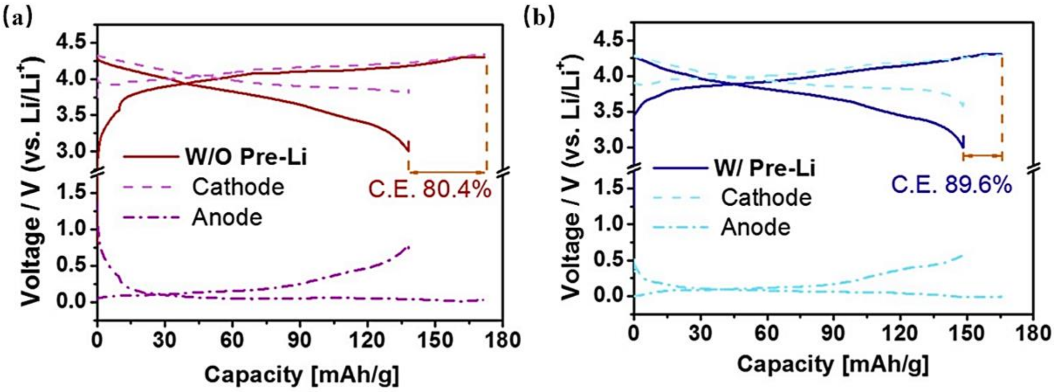

Figure 2. Capacity and initial efficiency of (a)W/O Pre-Li and (b)W/ Pre-Li [6].

3.2. Binder

The role of the binder in lithium-ion batteries with silicon anodes is of utmost importance. It plays a critical role in the embedding and dislodging process of silicon, which undergoes significant changes in volume. The binder ensures the stability of the electrode structure and, to some extent, enhances its conductivity. Different types of binders are selected based on the specific requirements of each battery.

These binders can be broadly categorized into four groups according to their characteristics. Non-conductive binders, such as polyvinyl alcohol (PVA) and polyvinyl acrylate (PVDF), contribute viscosity to enhance structural stability but lack electrical conductivity. Conductive binders, such as polypyrrole (PPy) and poly(3,4-ethylenedioxythiophene) (PEDOT), not only maintain structural stability but also exhibit favorable electrical conductivity. One can find complex green chemistry binders derived from natural biomaterials, including sodium hyaluronate (SA) sourced from brown algae. Furthermore, self-healing binders that are capable of repairing their own structure when the electrodes sustain damage are also being explored.

To create high energy density silicon-based anode lithium-ion batteries, it is crucial to prioritize electrodes with high electrical conductivity. Additionally, the binder used must possess properties similar to those of the conductive polymer binder. It is common practice to combine different binders to achieve desired outcomes.

Michael et al. combined poly(3,4-ethylenedioxythiophene (PEDOT):poly(4-styrenesulfonic acid (PSS) with polyethylene oxide (PEO) to create a composite material with exceptional electron and ion transport properties. This composite conductive binder offers the advantages of both binders, including structural stability and high conductivity, making it an urgently needed binder in the current stage. This material is a composite conductive binder, retaining the advantages of both, both structural stability and high conductivity, is the current stage of the urgent need for a class of binder. Lithium-ion transport occurs mainly in the amorphous region of the polymer, and when PEO crystallises, the transport channels are reduced. By changing the PEDOT-PEO ratio, it was found that PSS inhibits the crystallisation of PEO and improves the conductivity of the electrode. In addition, the study revealed a strong interaction between PEO and PSS, promoting a more uniform distribution of the two components. This interaction facilitated the formation of a more organized and concentrated network structure for PEDOT, thereby enabling higher rates of lithium-ion passage [7].

4. Advancing methods of electrolytes

The current lithium-ion batteries are insufficient to meet the growing demands for increased energy density, enhanced power capability, and improved safety performance in large-scale applications. While scientists are investigating high-capacity and high-voltage cathodes (such as cathodes made of Ni-rich, Li-rich layered oxides and spinel $LiNi_{0.5}Mn_{1.5}O_4$) as well as high-capacity anodes (like anodes composed of Li-, Si-, and Sn-based materials), the critical issue lies in developing a compatible electrolyte for these electrodes.

4.1. High-voltage Lithium-Ion

Electrolytes play a vital role in the operation of lithium-ion batteries as they directly impact the behavior of electrochemical processes by interacting with the electrodes and influencing the diffusion of Li^+ ions. In addition to requiring high electrical conductivity and high ionic throughput, it is also important for electrolytes to be able to adapt to high voltages and have a wide electrochemical window. The energy difference between the highest occupied molecular orbital (HOMO) and the lowest unoccupied molecular orbital (LUMO) determines the electrochemical window of the electrolytes. When the potentials of the cathodes are lower than the HOMO of the electrolytes, electrons are transferred from the electrolytes to the cathodes, causing the oxidation of the electrolytes.

However, the traditional electrolytes face challenges in meeting the demands of high-voltage cathode materials as they tend to undergo oxidation at around 4.5 V. Although the oxidation potentials of organic carbonate solvents are approximately 5 V, the presence of transition-metal ions can act as catalysts for the oxidation reaction, leading to the rapid deterioration of electrolytes at lower potentials, thus resulting in a significant decrease in capacity [8]. Hence, it is imperative to search for electrolytes that are compatible with high-voltage LIBs. Current research on high-voltage electrolytes primarily focuses on exploring stable solvents and functional additives. An example of such a suitable electrolyte is room temperature ionic liquid (RTIL), which possesses several advantageous properties including high stability and low volatility. One of the most significant advantages of RTIL is its extensive electrochemical window of 5V or more. This means that the electrolyte can withstand a wider range of voltages without decomposing, resulting in increased stability and higher energy density at high voltage. To further enhance the electrolyte's ability to adapt to higher voltages, functional additives such as fluoride or borate esters can be added to certain organic carbonate solvents. These additives contribute to improved thermal and electrochemical stability of the electrolyte.

4.2. Improving qualities of SEI

In most lithium-ion batteries, lithium dendrite growth occurs due to the instability of the electrode interface and non-uniformity of the electrochemical reaction. This phenomenon leads to the formation of more dead lithium, resulting in a decrease in energy density and poor safety. In lithium-ion batteries, a solid electrolyte interface (SEI) film naturally forms during the initial charge/discharge process. Composed mainly of electrolyte decomposition products, this film acts as an insulating barrier on the anode surface, preventing direct contact between the electrolyte and anode material. Consequently, irreversible chemical reactions are reduced, improving battery cycling stability and minimizing electrolyte decomposition and loss of lithium ions.

However, naturally occurring SEI films can present some challenges, including uneven distribution, dynamic changes, and potential energy loss. The distribution of the SEI film on the anode surface may be uneven, leading to localized areas that are either too thick or too thin. This can hinder the transport of lithium ions and impact battery performance. The naturally formed SEI film may undergo structural changes during charging and discharging cycles, such as increased thickness and altered composition. These changes can gradually decrease battery performance. Although naturally formed SEI films can prevent irreversible reactions, they can still result in some energy loss. This is because the formation of SEI films requires the consumption of lithium ions and electrolyte, which reduces the battery's first reversible capacity. To improve the properties of SEI films, there are two methods: additives and changing the substance of electrolytes.

4.2.1. Additives. Additives play a vital role in promoting the development of stable interfacial films, also known as SEI films, on the surface of the electrode. These films are crucial for preventing the breakdown of the electrolyte and undesired reactions on the electrode surface. The primary function of additives is to induce the formation of interfacial films through electro-polymerization. This process not only enhances the conductivity of the cathode material but also inhibits the catalytic decomposition of the electrolyte by transition metal ions. Additionally, certain additives effectively hinder the decomposition of the electrolyte under high voltage conditions, thereby enhancing the thermal and electrochemical stability of the electrolyte. Ultimately, this improvement leads to enhanced safety and overall performance of high voltage batteries. A notable example is LiBOB, an electrolyte that forms a protective layer against oxidation on the cathode surface when oxidation occurs which ads in the formation of stable SEI films on anodes. At the same time, a thin surface film is formed and the impedance is reduced [9]. These reduction reactions, along with low resistance and active materials, contribute to improved ion conductivity, resulting in increased energy density and a higher number of recycling cycles. LiBOB serves as a viable alternative to $LiPF_6$, which is not without its drawbacks. As a lithium salt, LiBOB effectively inhibits the production of trace HF and the dissolution of metal ions on the cathode surface caused by HF corrosion. This property ultimately safeguards the cathode material, leading to enhanced stability and longevity of the battery.

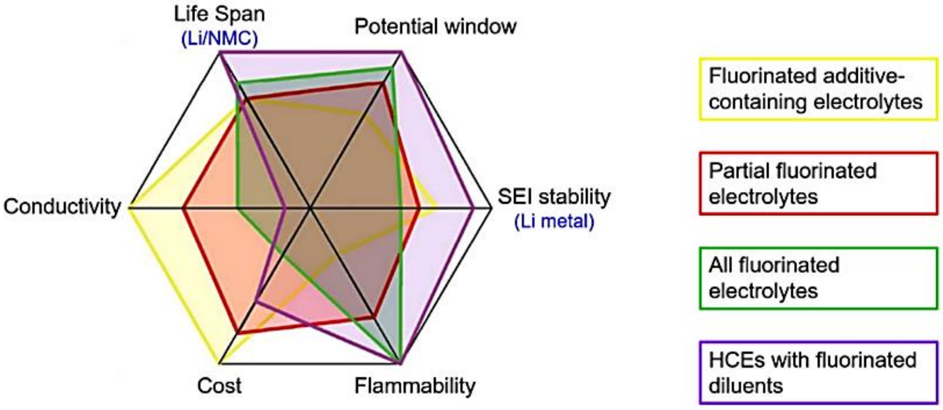

Figure 3. Comparison of electrochemical properties among electrolytes with different fluorine concentrations [10].

4.2.2. Changing substance. When it comes to changing electrolytes, different electrolytes offer unique advantages in lithium-ion battery applications. An example of this can be seen in non-aqueous liquid electrolytes that incorporate fluorinated compounds. These electrolytes possess properties such as high oxidative stability, low melting points, and good wettability. They can also establish effective contact with diaphragms and electrodes [9]. For the purpose of increasing the energy density of lithium-ion batteries, fluorinated compounds (such as Fluorinated carbonates, fluorinated phosphates, and fluorinated sulphates) are regarded as ideal electrolyte compositions. Figure 3 reveals that electrolytes with different fluoridation degrees have different advantages in different characteristics and can be selected according to specific needs. One of the reasons for this is their high oxidative stability, which allows them to withstand high voltages without decomposing. Additionally, these compounds have lower melting points, ensuring good fluidity even at lower temperatures. As a result, battery performance is improved at low temperatures, including enhanced lithium-ion transport rate and battery charge/discharge capability. Moreover, fluorine-containing compounds have better contact with the diaphragm and electrodes, reducing interfacial resistance and improving the lithium-ion transport rate within the battery. This improved contractibility also contributes to the cycling stability of the battery by minimizing side reactions caused by electrolyte decomposition. Moreover, exceptional stability is displayed by these compounds at the interface between the electrode and electrolyte containing LiF, which includes both the solid electrolyte interphase (SEI) and cathode electrolyte interphase (CEI) [10]. Compounds containing fluorine have the ability to enhance the formation and durability of SEI layers through their interaction with lithium ions, resulting in the creation of compounds like LiF, which are highly stable and insoluble.

5. Conclusion

This research paper presents a comprehensive overview of advanced approaches aimed at improving the energy density of lithium-ion batteries. It explores multiple aspects including the positive and negative electrodes, as well as electrolytes. Notably, promising progress has been made in enhancing the energy density and practical applications of cathode materials, particularly with the use of high nickel NMA and LFP. While the research on negative electrode materials remains relatively limited, the utilization of novel materials like silicon-based materials and silicon-graphite composites has demonstrated their potential for boosting energy density. Furthermore, cutting-edge methods for electrolyte enhancement, such as the combination of RTIL with traditional carbonate solvents and co-solvents, as well as the modification of the solid electrolyte SEI through the incorporation of additives or alteration of the electrolyte substance (such as fluorine compounds), offer great promise for future development. Despite the significant challenge involved in increasing the energy density of lithium-ion batteries, their potential in the field of power batteries has already been firmly established. Due to their energy density, cost, and numerous other advantages, lithium-ion batteries are projected to maintain their dominance in the battery market for the foreseeable future.

The market indicates that the reform of high-capacity power batteries is already underway, with a significant demand emerging in various environments, societies, and individuals. There is a continuous pursuit to push the boundaries of lithium-ion battery energy density and explore the potential of alternative high-energy-density batteries, making it a global challenge that requires breakthroughs. Emphasizing meticulous attention to every detail becomes the sole option available to us.

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