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Comparison of Different Nanomaterials in Anode Materials of Lithium Battery

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Abstract: The increasing demand for sustainable energy necessitates the enhancement of lithium-ion battery technology, especially in the advancement of superior anode materials. Contemporary lithium-ion batteries exhibit specific constraints, including comparatively poor energy density and restricted cycle life, which have stimulated growing interest in alternative battery materials with superior performance. This research conducts a literature analysis to investigate the potential of several nanomaterials—graphene, clay mineral-derived materials, and transition metal sulfides—as improved anode materials for lithium-ion batteries. The study analyzes their characteristics, including energy storage capacity, charging speed, and cycling stability, emphasizing both their benefits and drawbacks. The study concludes that although these materials enhance battery performance considerably, obstacles persist regarding their commercialization and long-term stability. This research provides significant insights into the advancement of more efficient and sustainable lithium-ion battery technology, facilitating the global shift to renewable energy.

Keywords: nanomaterials, lithium battery, anode materials.

1. Introduction

With the rapid development of economy and industrialization, global energy demand continues to rise, and fossil fuels such as coal and oil still occupy a dominant position of more than 80% in energy consumption. Although the wide application of fossil energy has greatly promoted the progress of human civilization, it has also led to the rapid reduction of fossil resource reserves, making fossil energy face the dilemma of shortage. At the same time, the consumption of fossil energy is accompanied by the emission of toxic gases (CO carbon monoxide, SO_2 sulfur dioxide, etc.) and greenhouse gases, which not only causes ocean temperatures to rise, ocean water acidification, but also makes the ice at the poles of the Earth melt faster and faster year by year. Therefore, people pay more attention to the development and utilization of renewable energy. A very important example is new energy vehicles (NEVs). Nowadays new energy vehicles (NEVs) can become common in society.

For New Energy Vehicles (NEVs) to effectively supplant conventional automobiles, a critical advancement in battery energy technology is essential to address the issue of range anxiety. Currently, lithium-ion batteries (LIBs) are extensively utilized in NEV-power batteries. Nonetheless, the restricted theoretical capacity of commercial graphite as an anode material for lithium-ion batteries (372 $mAhg^{-1}$) is inadequate to satisfy the escalating human demand for energy storage; thus, it is

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imperative to investigate and develop anode materials for lithium-ion batteries that possess higher capacity, accelerated charging rates, and extended cycle life.

A B Yaroslavtsev, T L Kulova, and A M Skundin examined the cutting-edge technology of anode nanomaterials for lithium-ion batteries (LIBs) [1]. These nanoparticles facilitate elevated charge and discharge rates, mitigate the detrimental impact of degradation processes resulting from volume fluctuations in electrode materials during lithium intercalation and deintercalation, and augment the power and operational capacity of lithium-ion batteries.

Junqin Zheng constructed nanocomposites by combining metal sulfides with carbon-based materials and applied them to lithium-ion anode materials [2]. Thus, the lithium-ion and electron diffusion ability of the composite material is enhanced, and the rate performance and long-cycle stability of the electrode material are improved.

This paper is highly significant in addressing the global shift towards sustainable energy solutions, particularly in the field of new energy vehicles. By focusing on advanced anode materials for lithium-ion batteries, this study contributes to providing a lot of information on overcoming critical challenges like energy storage capacity, charging speed, and battery lifespan. This research not only advances the technological capabilities of LIBs but also supports the broader transition from fossil fuels to renewable energy sources. It offers valuable insights and potential breakthroughs that could accelerate the progress in the battery performance of NEVs, thereby reducing the environmental impact of transportation and supporting global sustainability goals.

2. Principle of Lithium-Ion Battery

Lithium-ion batteries are apparatuses that transmute chemical energy into electrical energy and vice versa. The fundamental components of the lithium-ion battery system include the positive and negative electrodes, electrolyte, separator, support material, and case. The prevalent cathode materials include lithium compounds, including lithium iron phosphate ($LiFePO_4$), lithium nickelate ($LiNiO_2$), and lithium manganate ($LiMnO_2$). Among the anode materials, graphite is currently the most commonly used commercially. Graphite is currently the most affordable anode material due to its abundant resources and affordable price [3].

As clearly shown in Figure 1, the lithium-ion battery is charged and discharged by the movement and conversion of lithium ions between positive and negative electrodes.

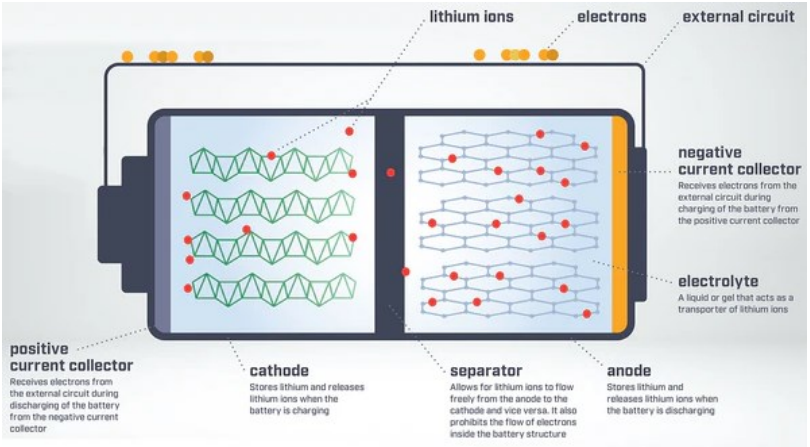


Figure 1: Discharge of a lithium-ion battery

The electrode reactions in a Na-ion battery utilizing hard carbon(C6) anode and a layered transition metal oxide, $NaMO_2$, cathode is depicted like:

$Na_xC_6+Na_{1-x}MO_2 \leftrightharpoons NaMO_2+C_6$

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Cathode:
$CoO_2+Na^++e^- \leftrightharpoons NaCoO_2$
Anode:
$NaC_6 \leftrightharpoons C_6+Na^++e^-$

3. Different Nanomaterials of Anode

3.1. Graphene

Graphene, a sp2 hybridized monolayer two-dimensional nanomaterial, is a favored anode material due to its high theoretical specific capacity (744 $mAhg^{-1}$), exceptional conductivity, and extensive specific surface area. Nonetheless, graphene possesses certain drawbacks; specifically, it is susceptible to volumetric fluctuations during the charging and discharging phases, resulting in structural degradation that adversely impacts the battery's cycle life and stability. Furthermore, the extensive surface area of graphene results in the formation of a thicker solid electrolyte interface (SEI) film during the initial charge/discharge cycle, thus leading to an increase in the irreversible loss of first charge capacity.

3.2. Clay Mineral Derived Nanomaterials

3.2.1. Structure and Characteristics of Clay minerals

Clay minerals generally refer to layered silicate minerals that impart plasticity to clay and harden upon drying or firing. Their crystal structure is primarily composed of two fundamental structural layers: the tetrahedral sheet (T layer), made of silica, and the octahedral sheet (O layer), composed of aluminum or magnesium oxides. Based on the stacking and proportion of these two structural layers, clay minerals can be categorized into two types: 1:1 type (TO) and 2:1 type (TOT) [4]. In addition, there is a special class of clay minerals known as hydrotalcite. The three-dimensional crystal structure of hydrotalcite is formed by the orderly longitudinal arrangement of nanoscale two-dimensional positive octahedral layers.

3.2.2. Clay Mineral-Derived Carbon-Based Nanomaterial

Clay minerals, as ideal template materials, have unique advantages in the preparation of carbon nanomaterials. Research has shown that montmorillonite, a typical two-dimensional layered clay mineral, can facilitate lithium-ion diffusion. Sandí and colleagues utilized natural montmorillonite, a type of clay mineral, as an inorganic template and achieved highly disordered carbon materials through pyrolysis at 700°C [5]. When used as an anode material for lithium-ion batteries, these carbon materials demonstrated a high specific capacity of up to 825 mA·h/g, with a capacity retention rate of 90% even after 20 cycles. The carbon nanosheets interspersed within the montmorillonite layers not only provide high electron transport channels but also enhance the mechanical properties of the composite material.

Chen and his team synthesized highly ordered two-dimensional montmorillonite/carbon nanocomposites utilizing montmorillonite and 3,3'-diaminobenzidine as precursors by intercalation, polymerization, and carbonization methods [6]. The interlayer architecture of montmorillonite/carbon nanosheets offers more open channels and active sites for lithium-ion transport, hence improving the performance of the composite material as a cathode in lithium-ion batteries. This composite, utilized as an anode material for lithium-ion batteries, demonstrates high reversible specific capacities of 1,432 mA·h/g at a current density of 0.05 A/g and 920 mA·h/g at 10 A/g, retaining 94% of its capacity after 50 cycles.

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In general, these two examples demonstrate the promising application of clay mineral-derived carbon-based nanomaterials as anode materials in the field of lithium-ion batteries.

3.2.3. Clay Mineral-Derived Silica-Based Nanomaterials

Silicon is considered a next-generation anode material for lithium-ion batteries, with a theoretical specific capacity of up to 4,200 mA·h/g, making it the highest known anode material in terms of specific capacity [7]. Unlike the intercalation mechanism of carbon materials, the lithium storage mechanism of silicon anodes involves alloying and dealloying reactions between lithium ions and silicon. The reactions during the charge and discharge processes are as follows:

$$Si + xLi^{+} + xe^{-} \rightleftharpoons Li_xSi$$

Extensive research has yielded numerous experimental findings concerning the application of silicon nanoparticles as anodes in batteries. One-dimensional silicon nanorods derived from natural sepiolite exhibit significant capacities as anodes for lithium-ion batteries, sustaining a capacity of 1,350 mA·h/g after 100 cycles at 1.0 A/g, and preserving 816 mA·h/g after 500 cycles at 5.0 A/g, with a capacity retention rate of 98%. Furthermore, zero-dimensional silicon nanoparticles, two-dimensional porous silicon, and three-dimensional silicon frameworks have been synthesized utilizing palygorskite attapulgite, montmorillonite, and halloysite. All three varieties of silicon materials demonstrate commendable electrochemical performance as anodes for lithium-ion batteries, with two-dimensional porous silicon exhibiting exceptional cycling stability (retaining a specific capacity of 1,369 mA·h/g after 200 cycles at 1.0 A/g, achieving a capacity retention rate of 78%).Overall, clay mineral-derived silicon-based nanomaterials show great potential for application in the anode field of lithium-ion batteries. Table I below demonstrates the electrochemical properties of clay mineral-derived silicon-based nano-negative materials.

Table 1: electrochemical properties of clay mineral derived silicon-based nano-negative materials

Clay minerals	Silicon-based anode materials	Cycling properties	Rate properties
Sepiolite	Silicon nanorods	1.0 A/g,1 350 mA·h/g (100 cycles)	10.0 A/g,478 mA·h/g
Halloysite	Silicon nanotubes	0.2 A/g,3 044 mA·h/g (1 cycle) 1.0 A/g,1 033 mA·h/g (1 000 cycles)	2.0 A/g,947 mA·h/g
Talc	Porous silicon nanosheets	1.0 A/g,1 303 mA·h/g (500 cycles)	1.0 A/g,1 985 mA·h/g
Halloysite	Si	1.0 A/g,3 752.4 mA·h/g (1 cycle) 3.5 A/g,1 469.0 mA·h/g (400 cycles)	10 A/g,1 050 mA·h/g
Montmorillonite	Silicon flake/nitrogen-doped graphene-like carbon composite	1.0 A/g,1 138 mA·h/g (240 cycles)	8.0 A/g,434 mA·h/g

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3.3. Transition Metal Sulfide (TMSs)

TMSs are known for their high electrochemical capacity due to their various valence states and crystal structures. Compared to other corresponding transition metal oxides, TMSs have better electrical conductivity and thermal stability, and exhibit less volume expansion during the lithiation process. Additionally, the high voltage platform of TMSs can effectively prevent the formation of lithium dendrites, ensuring the safety of LIBs. The low cost of raw materials and the unique physical and chemical properties make transition metal sulfides a popular choice for LIB anode materials.

3.4. Iron-Based Sulfide

Iron-based sulfides, including FeS (609 mA·h/g) and FeS_2 (890 mA·h/g), can participate in conversion processes with lithium ions during cycling when utilized as anodes in lithium-ion batteries. Their stratified composition (S-Fe-S) promotes rapid lithium-ion transport, rendering iron-based sulfides viable candidates for lithium-ion battery anodes.

The FeS_2/rGO composite electrode, produced by a solvothermal technique, has a microsphere structure that markedly decreases the charge transfer resistance of FeS_2 and improves the stability of the electrode architecture. This composite electrode demonstrates a remarkable reversible capacity of 970 mAh/g after 300 cycles at a current density of 0.89 A/g. After 2,000 cycles at 8.9 A/g, the capacity persists at 380 mAh/g, indicating exceptional cycling performance.

The layered structure of the FeS nanoparticle/carbon nanosheet composite material augments electrical and ionic conductivity. It demonstrates a reversible capacity of 703 mAh/g following 150 cycles at a current density of 1 A/g [8]. This capacity is markedly enhanced relative to the material lacking a layered structure.

4. Discussion

Although several novel anode nanomaterials have their advantages, they also come with certain drawbacks. The disadvantages of graphene have already been discussed above. Now, we will focus on discussing the drawbacks of clay mineral-derived nanomaterials and transition metal sulfides when used as anodes.

The structure of carbon nanomaterials prepared with clay minerals as inorganic templates depends on the structure of the inorganic templates themselves, and the structure of silica-based materials derived from clay minerals is also closely related to the clay minerals themselves. The structure and quality of clay minerals from different geographic environments or different mineral sources are different, and even if the same clay minerals have different origins and purification methods, it is difficult to ensure the uniformity of the structure and performance of the carbon and silica materials made from the same clay minerals. The commercialization of carbon-based and silicon-based nanomaterials from clay minerals requires strict control of their properties, which poses a challenge to the commercialization of carbon-based and silicon-based nanomaterials derived from clay minerals.

Challenges remain in attaining high-performance transition metal sulfides, including inadequate electronic and ionic conductivity, which significantly impairs the electrode's power density. Furthermore, during the lithiation/delithiation process, transition metal sulfides experience considerable structural reorganization, resulting in substantial volume expansion and diminished cycling stability.

5. Conclusion

The research examines several nanomaterials employed in anode applications for lithium-ion batteries, with particular emphasis on graphene, clay mineral-derived substances, and transition metal sulfides.

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These materials exhibit potential in improving energy storage capacity, charging velocity, and cycle longevity, which are essential for the advancement of NEVs. Graphene and clay mineral-derived nanomaterials have benefits such as elevated conductivity and stability; yet, their commercialization encounters obstacles concerning structural regularity and volumetric alterations throughout charge cycles. Transition metal sulfides exhibit substantial electrochemical capacity; nonetheless, they are hindered by conductivity challenges and volumetric expansion, which compromise cycling stability.

Nevertheless, the research is deficient in extensive experimental validation and wider real-world testing, hence constraining its applicability. Future research will concentrate on refining the synthesis procedures of these nanomaterials and performing comprehensive performance assessments under diverse settings. Furthermore, augmenting the consistency of clay mineral-derived materials and raising the conductivity of transition metal sulfides are critical domains for additional investigation. The results establish a basis for future progress in lithium-ion battery technology, aiding the larger transition to sustainable energy sources and mitigating the environmental effects of transportation.

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