Enhancing Battery Performance and Safety Through Nanomaterial Coatings

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Abstract. The global transition to electric vehicles (EVs) is crucial for reducing carbon dioxide (CO_2) emissions and combating climate change. Although EVs offer environmental and economic advantages, battery performance challenges such as electrode degradation and electrolyte decomposition hinder their widespread adoption. This paper investigates the use of nanomaterials in battery coatings and membranes to improve EV battery performance and lifespan. Conductive polymers like Polyaniline (PANI), carbon-based materials such as g-C_3N_4/CNTs, and α-Fe_2O_3@C are explored for their capacity to enhance electrode stability, electrical conductivity, and specific capacity. Additionally, the paper addresses how nanocoatings mitigate issues like electrode degradation, parasitic reactions, and thermal management, ultimately extending battery life and improving safety. By integrating nanotechnology, significant advancements in battery efficiency, longevity, and safety can be achieved, making EVs a more viable and sustainable transportation option. These developments are essential for achieving global carbon reduction goals and supporting a cleaner future.

Keywords: Nanotechnology, battery performances, nanocoating

1. Introduction

In response to reducing global Carbon Dioxide (CO_2) emissions and mitigating climate change, electric vehicles (EVs) have become a new transportation method that is slowly taking over internal combustion engine vehicles [1]. EVs are gradually being accepted by consumers due to their low CO_2 emissions, low maintenance costs, and low recharge costs [2].

Nonetheless, several drawbacks to EV batteries negatively impact their performance. Electrode degradation is one severe issue that causes the battery to lose energy storage [3]. In other words, the battery life of EVs will gradually reduce over time, leading to reduced travel range and a more frequent charging rate. Additionally, electrolyte decomposition is another significant issue affecting the batteries' longevity. The electrolyte breaks down and forms harmful byproducts, reversely affecting the battery's performance [4]. This happens when the battery is experiencing high temperature, overcharging, or repeated charging [4].

To counter the persistent issues that reduce battery performance, nano-coating technologies have made critical improvements in various aspects. Scholars have found that nano-coatings can improve energy density, enhance battery life, and increase charging rates [5]. Integrating nano-coating technology provides unique advantages compared to traditional materials due to the infinitesimal scale. Specifically, the increased effective surface area of the anode particles can facilitate better electrochemical reactions and improve battery efficiency [6].

The objective of this paper is to introduce the typically used nanomaterials as battery coatings and membranes and discuss how nanomaterials enhance battery performance, including improved electrode stability, improved electrical conductivity, and enhanced battery efficiency.

2. Nanomaterials Used in Battery Coatings and Membranes

2.1. Conductive Polymers

Conductive Polymers are commonly used to coat the electrodes of batteries. To be more specific, Polyaniline (PANI) is a widely used conductive polymer due to its high conductivity, reversible convertibility between redox states, and beneficial structural specificality [7]. Additionally, the flexibility of PANI coating prevents the anode material from cracking and accelerates the electrode transfer rate, resulting in enhanced electrochemical performance [8].

Researchers coated PANI uniformly on the LiV_3O_8 nanorods, an anode material for Lithium-ion batteries, and synthesized LiV_3O_8-PANI nanocomposite [9]. Figure 1A compares LiV_3O_8-PANI nano-composite and LiV_3O_8 nanorods in terms of discharge capacity from 0 cycles to 100 cycles at 0.1 C. The black dotted line represents the discharge capacity of LiV_3O_8 nanorods, which steadily decreases initially from approximately 280mAh/g to 110mAh/g after 100 cycles, with a slight bump at the 70th cycle. Moreover, the blue, red, and purple dotted lines represent LiV_3O_8-PANI nano-composite when PANI is synthesized with diverse weight percentages. It is safe to conclude that LiV_3O_8-PANI nanocomposite with 12 wt. % PANI (red dotted line) performs the best among the three products since it has the smallest negative slope—additionally, the discharge capacity of LiV_3O_8 -12 wt. % PANI initially starts at 240mAh/g and gradually declines to 225mAh/g after 100 cycles, indicating the discharge capacity loss is merely 15mAh/g.

In order to prove the composite is a better material than LiV3O8 nanorods, the discharge capacity is compared at diverse coulomb rates. Figure 1B compares discharge capacity between composites and LiV_3O_8 nanorods at 0-30 cycles from 0.2C to 4C. The Figure indicates that the composite processes a higher discharge capacity than LiV_3O_8 nanorods at different cycles except for the initial cycle. This phenomenon can also be shown in Figure 1A, where LiV_3O_8-12 wt. % PANI initially starts at 240mAh/g, and LiV_3O_8 nanorods start around 280mAh/g.

Thus, from the experiment, it is reasonable to conclude that LiV_3O_8-PANI nano-composite processes higher discharge capacity and better electrical conductivity compared to traditional LiV_3O_8 anode material. The improved electrical performance is achieved since the PANI coating can buffer the dissolution in LiV_3O_8 during cycling, and the PANI coating composite electrode has lower charge transfer resistance than the LiV_3O_8 nanorods electrode [9].

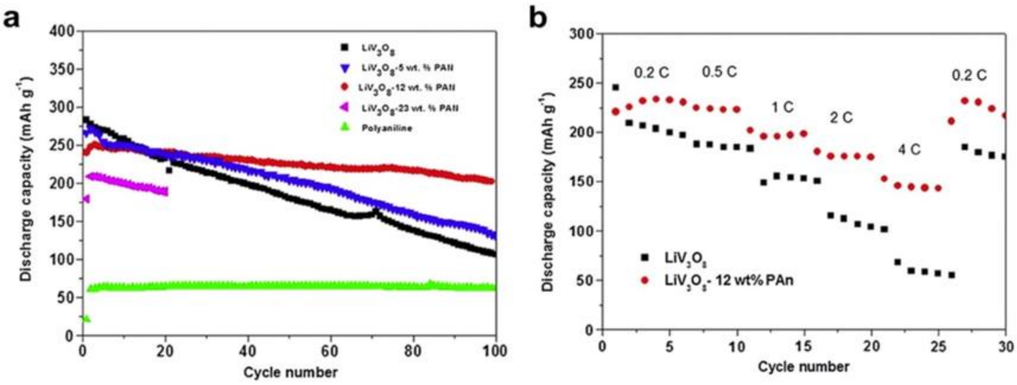

Figure 1. Comparison between LiV_3O_8-PANI nano-composite and LiV_3O_8 under different conditions [9]

2.2. Carbon-based materials

Graphitic carbon nitride (g-C_3N_4) is one of the most suitable materials for free-standing cathode in Lithium–sulphur batteries since it not only possesses a particular chemical structure but also has rich Nitrogen content [10]. Precisely, the unique, multilayered structure fulfilled with heptazine units ($C_6N_7H_3$) is connected by Vander Waals forces, ensuring the excellent ability to trap polysulfides. In order to improve the electro-conductivity of g-C_3N_4, scholars have designed a synthesized method to combine g-C_3N_4 with carbon nanotubes (CNTs), forming graphitic-carbon nitride/carbon nanotubes (g-C_3N_4/CNTs) hybrid membrane [10]. Furthermore, the CNTs act as electron mediators due to their high electronic conductivity. Figure 2 below shows the overall structure of the g- C_3N_4/CNTs hybrid membrane. The uniformly distributed CNTs act as a base that holds the g-C_3N_4. Sufficient hollow areas in the structure ensure effective electron and lithium-ion transportation.

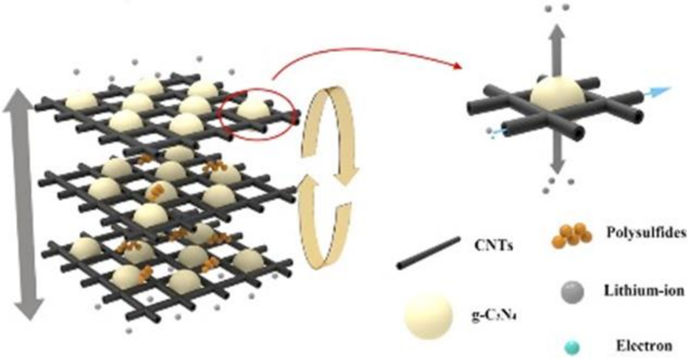

Figure 2. Schematic illustration of free-standing graphitic- carbon nitride/carbon nanotubes (g-C_3N_4/CNTs) membrane in the Li/polysulfides cell [10]

Moreover, Figure 3A shows cycle stability and Coulombic efficiency of the traditional CNTs and g-C_3N_4/CNTs composite electrode at 0.5 Coulomb rate for 300 cycles. The CNTs alone have an initial specific capacity of 700mAh/g and linearly decreases to 300mAh/g mass after 300 cycles with an average coulombic efficiency of 95%. In comparison, the g-C_3N_4/CNTscomposite has an initial specific capacity of 900mAh/g and gradually decreases to 600 mAh/g with an average coulombic efficiency of 98%. This shows that the g-C_3N_4/CNTs hybrid membrane has a higher overall specific capacity and average coulombic efficiency than the CNTs at 0.5 Coulomb rate. Furthermore, for the preciseness of the result, scholars compare the specific capacity at diverse coulomb rates. Figure 3B shows that the composite has a higher specific capacity than CNTs from 0.1C to 1C.

Therefore, a hybrid membrane composed of g-C_3N_4/CNTs proves to be an exceptional material for electrodes in lithium-sulfur batteries, owing to its high specific capacity, superior coulombic efficiency, effective suppression of self-discharge, and excellent lithium polysulfide absorption. Furthermore, the enhanced electrochemical performance of this hybrid membrane facilitates more efficient energy storage and retrieval [10]. Consequently, the graphitic carbon nitride and carbon nanotube hybrid membrane is a viable production design for high-energy-density devices [11].

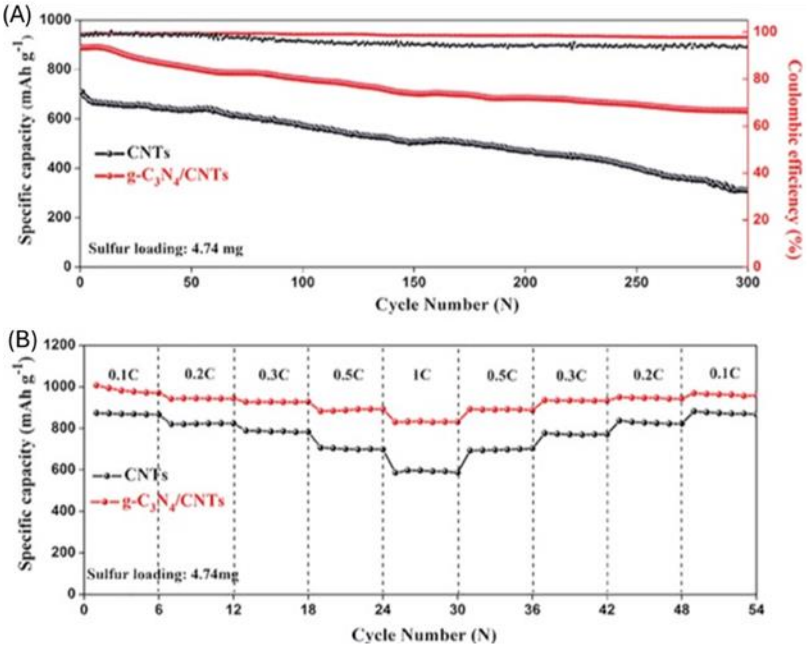

Figure 3. Performance comparison of the traditional CNTs and g-C_3N_4/CNTs composite electrode [10]

2.3. Metal Oxide-Based Materials

For lithium-ion batteries, alpha-ferric oxide (α-Fe_2O_3) is a promising anode material due to its high theoretical capacity, natural abundance, non-toxicity, cost-efficient, and environmentally friendly

[12]. However, the primary challenges associated with α-Fe_2O_3 are its weak electronic conductivity and significant volume expansion during the lithiation process, which hinders its application in battery technology [13]. Scholars came up with a solution that is a carbon-coated alpha ferric oxide (α-Fe_2O_3@C). Figure 4 below shows that the coating layer dopamine ($C_8H_{11}NO_2$) is coated on the surface of α-Fe_2O_3.

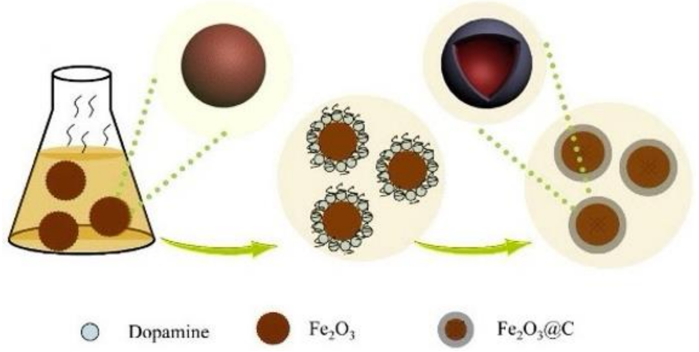

Figure 4. Performance comparison of the traditional CNTs and g-C_3N_4/CNTs composite electrode [10]

To achieve the best possible performance of α-Fe_2O_3@C, scholars have synthesized α-FC-300 through an annealing process with inert gas Argon (Ar) after carbon coating [13]. Figure 5 illustrates the efficiency vs. cycle number of α-FC-300 and conventional α-Fe_2O_3 at current density 1C. The Figure demonstrates that α-FC-300's charge efficiency is almost constantly maintained at 100%, and the discharge efficiency fluctuates from 70% to 45%. The charge efficiency of normal α-Fe_2O_3 fluctuates from 70% to 45%, while the discharge rate is only approximately 10%. By comparison, α-FC-300 is a lot more efficient than the traditional α-Fe_2O_3.

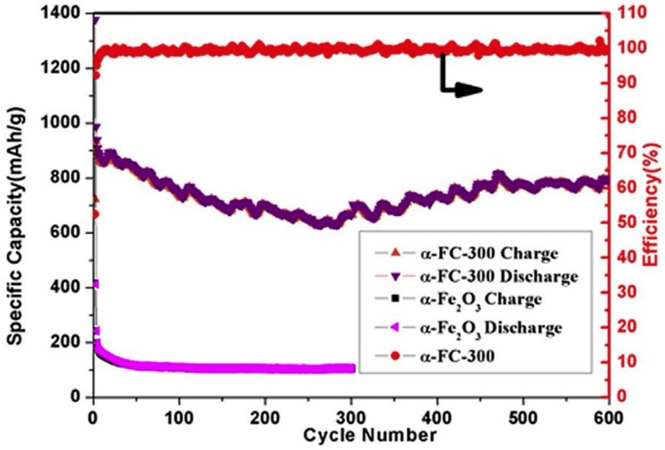

Figure 5. Cycle performance of α-Fe_2O_3 and α-FC-300 hollow spheres at the current density of 1C [13]

Hence, based on Figure 5, α-FC-300 demonstrates superior charge and discharge efficiency compared to conventional α-Fe_2O_3, proving that the carbon coating is critical in enhancing its electrical conductivity [13].

3. Advances in Silicon Nanomaterials

Battery cycle life can be significantly enhanced through the strategic application of nanocoatings, which address key challenges such as electrode degradation, parasitic reactions, and solid electrolyte interface (SEI) stability. This section summarizes the role of various nanocoatings in improving battery performance and longevity.

3.1. Improved Electrode Stability

Nanocoatings play a crucial role in protecting electrode materials from degradation, enhancing ion transport, and maintaining structural integrity throughout charge-discharge cycles. For instance, the CNT and ceramic-based layers provide robust mechanical protection by absorbing physical stress and strain during volume changes, which prevents cracking and pulverization of the electrode material, preserving its structural integrity and extending battery life. Further, conductive polymer coatings, such as polypyrrole and PEDOT, enhance electrical conductivity and act as barriers, preventing the electrode material from direct exposure to the electrolyte. This reduces side reactions and enhances overall electrochemical stability. Additionally, metallic oxide coatings like titanium oxide and aluminum oxide improve ion transport properties at the electrode surface. The nanocoatings facilitate faster lithium-ion diffusion and create a stable interface, minimizing resistance and boosting the electrode's rate capability.

3.2. Suppression of Parasitic Reactions

Nanocoatings effectively act as barriers to undesirable side reactions, thereby extending the battery's lifespan. Nanocoatings materials such as alumina and silica protect electrode surfaces from reacting with the electrolyte, reducing decomposition and preserving electrolyte integrity. Lithium dendrites are needle-like structures that can form on the surface of lithium metal anodes during repeated charge-discharge cycles in lithium metal batteries, which pose significant challenges to battery performance and safety. Nanostructured lithium-conductive ceramic coatings inhibit the growth of lithium dendrites in lithium metal batteries, preventing short circuits and enhancing safety. In addition, in lithium-sulfur batteries, coatings made from conductive polymers trap polysulfides, preventing them from dissolving into the electrolyte and migrating between electrodes. This mitigates capacity loss and improves cycle life.

4. Enhancement of Battery Cycle Life Through Coatings

4.1. Thermal Management Enhancements

Efficient thermal management is critical in preventing thermal runaway, a dangerous condition where the battery overheats uncontrollably. Nanocoatings such as graphene and graphene oxide, boron nitride (h-BN), and various metal oxides provide superior heat dissipation properties. Graphene and graphene oxide, known for their high thermal conductivity, effectively spread and dissipate heat generated during battery operation. Boron nitride (h-BN) complements these properties by offering excellent thermal stability and electrical insulation. Additionally, metal oxides like titanium oxide (TiO_2) and aluminum oxide (Al_2O_3) resist thermal degradation, maintaining their protective functions at high temperatures. These nanocoatings collectively help maintain optimal operating temperatures, preventing the onset of thermal runaway and enhancing overall battery safety.

4.2. Chemical Stability and Containment

Nanocoatings also play a crucial role in enhancing the chemical stability of battery components. Materials such as aluminum oxide (Al_2O_3), silicon dioxide (SiO_2), and ceramic-polymer composites provide robust chemical resistance, protecting the electrodes and electrolyte from corrosive reactions. Al_2O_3 and SiO_2 form impermeable layers that prevent the ingress of moisture and other contaminants, thereby reducing the risk of leaks. Ceramic-polymer composites offer a synergistic effect, combining the flexibility of polymers with the rigidity and chemical inertness of ceramics. These coatings not only enhance the longevity of the battery components but also contain hazardous materials, ensuring that they do not escape into the environment, thus contributing to safer battery operation.

4.3. Mitigation of Short-Circuit Risks

The prevention of internal short circuits is another critical aspect of battery safety, particularly in lithium metal batteries where dendrite formation is a common issue. Nanocoatings such as LiPON, CNTs, and composite ceramic coatings have shown effectiveness in mitigating this risk. LiPON, a solid electrolyte material, forms a stable interface with lithium metal, inhibiting the growth of dendrites. CNTs, with their high mechanical strength and electrical conductivity, provide a robust barrier that prevents dendrites from piercing through the separator. Composite ceramic coatings, which integrate various ceramic materials, offer a strong, dendrite-resistant layer that further reduces the likelihood of short circuits. By preventing dendrite growth, these nanocoatings help maintain the structural integrity of the battery and reduce the risk of catastrophic failures.

5. Conclusion

In summary, nanotechnology's role in advancing electric vehicle battery technology is exceptionally significant as it addresses the main difficulties and enhances overall performance. For instance, Polyaniline (PANI) is a conductive polymer coated on electrodes, leading to improved electrode stability and electrical conductivity. Furthermore, g-C_3N_4/CNTs and α-Fe_2O_3@C are carbon-based coatings which provide better specific capacity and efficiency for batteries. Nanomaterials like these have been used to address issues such as electrode degradation and electrolyte decomposition, which act detrimentally regarding the longevity of battery life. Thus, the usage of nanomaterials in batteries does not only lead to enhanced efficiency but also results in a considerably longer travel range. In the future, continued development towards nanomaterials for battery applications is needed in order to make electric vehicles a viable and more sustainable transport solution that supports achieving global goals of reducing carbon emissions to combat climate change.

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