A Review on The Application of Nano-Coated Si-Based Anode Materials for Lithium-Ion Batteries

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Abstract. This study examines three nano-coatings (carbon, metal, metal oxide) for silicon-based anodes. Those technologies were compared and the advantages and disadvantages were analysized. Nano-carbon coatings boost conductivity and reduce silicon's volume expansion but struggle under fast charging. Nano-metal coatings strengthen electrodes and block lithium dendrites but involve costly/toxic processes. Nano-metal oxide coatings reduce side reactions but face complex steps and delamination. All coatings share issues like weak bonding and high costs. Experiments suggest future focus on eco-friendly methods (e.g., water-based solvents), stronger bonding (e.g., chemical grafting), and scalable production. These upgrades could advance silicon anodes in fast-charging LIBs and EVs, supporting clean energy goals.

Keywords: Nano-coating Metarial, Coating Process Optimization.

1. Introduction

In recent years, with the booming development of the new energy vehicle industry and rising awareness of recycling and renewable energy, the demand for new types of batteries has been growing rapidly. As the keystone of energy storage technology, lithium-ion batteries (LIBs) have successfully dominated the power source fields. For the application of electric vehicles, it is urgent to develop next generation LIBs with bigger capacity, faster charging-discharging speeds, higher energy density safety, researchers in materials science have focused more on high-performance electrode materials.

In a basic lithium-ion battery system, the cathode, anode and electrolyte work together with the assistance of components such as the separator and case. With the development of lithium-ion battery technology, high performance electrode is in great need. The graphite, a traditional anode material, restricted by its limited theoretical capacity (372 mAh g-1) and low energy density (~150 Wh kg-1), is unable to meet the high requirements for performance, such as higher energy/power density and longer cycle life [1]. To overcome these bottlenecks, researchers have been actively investigating new electrode materials for lithium-ion batteries. These materials include $Li_4Ti_5O_{12}$, transition metal oxides (MnO_2, Nb_2O_5, NiO et al.), transition metal sulfides (Ni_2S_3, MoS_2, VS_2 et al.) and alloys [2]. Among them, silicon (Si) has been regarded as one of the most promising anode materials for high energy density lithium-ion batteries (LIBs) due to its high theoretical capacity, low discharge platform, and abundant reserves [3].

Silicon anodes show tremendous potential for the next generation of lithium-ion batteries based on their superior energy storage capacity. The highest theoretical capacity of Si (4200 mAh g^{-1}, 10 times more than graphite) is due to the fact that one Si atom can bond with approximately four lithium ions ($Li_{4.4}Si$) [4,5]. Meanwhile, Silicon higher operating voltage (0.4 V vs. graphite 0.05 V) helps suppress lithium dendrite growth and stabilizes the electrode interface (SEI layer), thereby significantly improving battery safety and cycle life [6]. In addition, silicon is widely distributed in nature, making it the second most abundantly stored element, and has benefited from the industrial development of the Si sector over the years, which has dramatically reduced application cost.

In typical graphite lithium batteries, lithium ions travel back and forth between the two electrodes of the battery in the electrolyte solution, and the charging and discharging processes are carried out through the lithiation and de-lithiation electrochemical reactions at the electrodes. In the lithiation process, lithium ions produced by the decomposition of lithium oxide in the anode move through the electrolyte to the cathode, where they combine with electrons to store energy. The de-lithiation

process is the opposite of this. Unlike the layered structure of graphite electrode materials, silicon-based materials have a three-dimensional spatial mesh structure. Although Si and graphite have the same mechanism for storing lithium, Si materials suffer noticeable volume changes (300-400%) during electrode operation, which generates mechanical stress, leading to active materials undergo cracking and pulverization, leading to electrical isolation and a marked decline in electrode performance and durability [7,8]. This is due to the alloying reaction of Si electrode. In the lithiation process, lithium ions firstly combine with the silicon atoms in the outer layer to form Li_xSi. With the movement of lithium ions, after the electrode voltage reaches 60 mV, the silicon will completely form the more stable $Li_{15}Si_4$, and finally complete the transformation from crystalline silicon to non-crystalline silicon. In addition, severe volume changes in repeated crushing and reorganization can irreversibly harm the stability of the solid electrolyte interphase (SEI) [9, 10]. Furthermore, severe volume changes can cause irreversible damage to the stability of the SEI during repeated crushing and reorganization of silicon electrode, ultimately leading to impaired battery performance. At the same time, the SEI is also depleted during charging and discharging, reducing the ability to transfer electrons, i.e., decreasing battery efficiency. To solve the issues, the nano-coating on Si-based materials was proposed through the design of nano-scale structures, which has also obviously improved the performance of the Si electrodes [11].

In order to solve this problem, researchers in recent years have investigated various nano-coating materials for silicon anodes. For instance, researchers demonstrated that carbon-coated silicon significantly enhances cycling stability and maintains structural integrity. Similarly, Liu et al. reported that metal oxide coatings effectively improve the initial coulombic efficiency and reduce side reactions. These studies collectively highlight the great potential of nano-coating strategies in addressing the limitations of silicon-based anodes [12]. This paper discusses the current research progress on various nano-coated silicon-based materials for anodes, especially when applied in the field of new energy vehicles. Firstly, it introduces the working of silicon-based anodes and the existing challenges, secondly, it compares the improvement of battery performance and the advantages and disadvantages of various coating materials (nano-Carbon, Nano-Metal, Nano-metal oxide) and synthesis methods, and it evaluates the challenges faced by the instant research and puts forward its own recommendations.

2. Case

2.1. Nano-Carbon coating

Nano-carbon coating materials refer to nanoscale carbon layers that form an encapsulated structure on the surface of silicon particles. This carbon layer provides a buffer against volume changes in silicon during cycling, improves electrical conductivity, and stabilizes the SEI layer. The common carbon materials used include amorphous carbon, graphene, and carbon nanotubes. Coatings are typically achieved by methods such as chemical vapor deposition (CVD), thermal decomposition, or sol-gel processes.

2.2. Nano-Metal coating

Nano-metal coating is a layer of compact metal encapsulation coated on the silicon surface, Such as Ni, Cu, and Ti, which enhances the overall structural strength and stability of the electrode, improving the conductivity and heat dissipation of the electrode interface in use, not only reducing internal resistance and improving thermal management, but also reducing the generation of lithium dendritic crystals and other reaction by-products. Coatings are typically achieved by methods such as electroplating, sputtering, chemical vapor deposition (CVD), and solution-based reduction techniques.

2.3. Nano-metal oxide coating

The Nano-metal oxide coating material is a unified nano-coating of metal oxide particles (TiO_2, Al_2O_3, SiO_2, ZnO, etc.) on the surface of silicon particles. Those dense coating enhances the initial

coulombic efficiency of the electrode by creating a physical barrier and inhibits the formation of side reactions. The Nano-metal oxide coating by physical or chemical methods such as sol-gel method, Atomic Layer Deposition (ALD) method, and so on.

3. Analysis&challenge

3.1. Nano-Carbon coating

The nano-carbon coating was synthesized through a chemical method [8]. Initially, 1 g of silicon nanoparticles was dispersed in 10 mL of diethylene glycol diacrylate phthalate aqueous solution (1 mg/mL) under continuous stirring at room temperature for 4 hours. The mixture was washed with deionized water, vacuum-dried at 40 °C for 24 hours, and then combined with 0.3 g of graphene and 0.7 g of poly-modified silicon nanoparticles in 100 mL of deionized water. The slurry was stirred at 40 °C for 4 hours, filtered, and dried in a vacuum oven. The resulting composite (0.1 g) was blended with 4 g of styrene-butadiene latex, ultrasonically treated for 30 minutes to form a homogeneous suspension, cast into a custom glass mold (50 mm × 50 mm × 2.3 mm), soft-baked at 40 °C, and annealed at 500 °C under Ar for 4 hours to produce the final graphene/silicon nanoparticles composite-coated silicon material, and showed in Fig. 1.
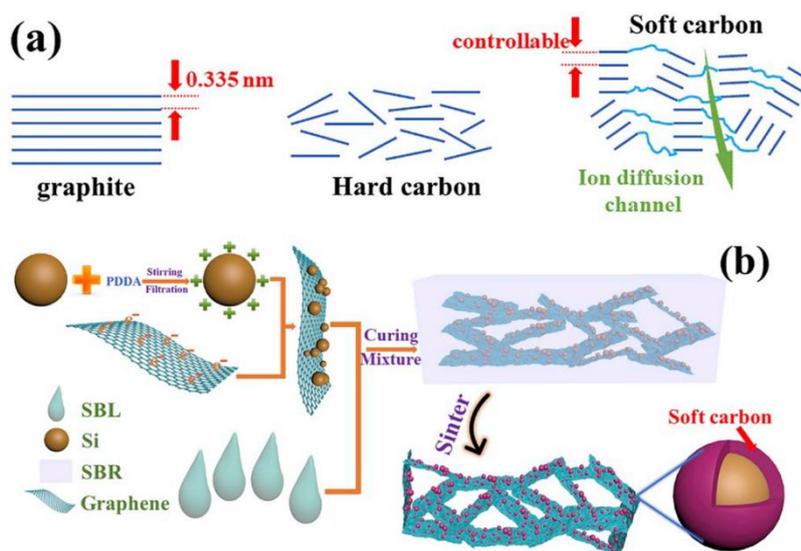

Fig. 1 the preparation of nano-carbon coated Si [8]

Electrochemical testing revealed that the composite exhibited a reversible specific capacity of 2636 mA h g^{-1} at low current density, with capacities gradually decreasing to 2516, 2236, 1843, 1518, and 1043 mA h g^{-1} as the current density increased. After 300 cycles, the capacity stabilized near 1100 mA h g^{-1}, demonstrating its ability to mitigate silicon's volume expansion during lithium-ion battery cycling. These results confirmed the effectiveness of the nano-carbon coating in enhancing electrode structural integrity [13].

Despite these advantages, challenges remain. Structural instability under high-current conditions limits its application in fast-charging batteries, while weak interfacial bonding between the carbon layer and silicon core restricts further capacity improvements. The use of toxic solvents, such as poly (diallyldimethylammonium chloride) and styrene-butadiene latex, raises environmental concerns, and parasitic side reactions during cycling reduce Coulombic efficiency. Future research must prioritize in situ characterization of coating dynamics, eco-friendly synthesis routes, and scalable manufacturing techniques to advance practical implementation.

3.2. Nano-Metal coating

To better address challenges in silicon-based anodes, a nickel-doped porous silicon (Ni-CPSi) composite was synthesized through sequential precipitation and thermal reduction processes [14]. The synthesis began with the preparation of nickel oxide-silica (NiO-SiO$_2$) precursors via a precipitation method. These precursors were then treated with magnesium-assisted high-temperature reduction at 700 °C under argon, where NiO and SiO$_2$ were converted into metallic nickel and silicon. During this stage, nickel silicide (NiSi$_2$) formed and migrated within the amorphous silicon matrix, inducing crystallization as illustrated in Fig. 2. Residual NiSi$_2$ was subsequently removed through acid etching, yielding a porous structure with nickel atoms embedded as dopants. The resulting material exhibited a tailored mesoporous framework and a controlled specific surface area of 104.5 m²/g, enhancing both ionic transport efficiency and structural stability.
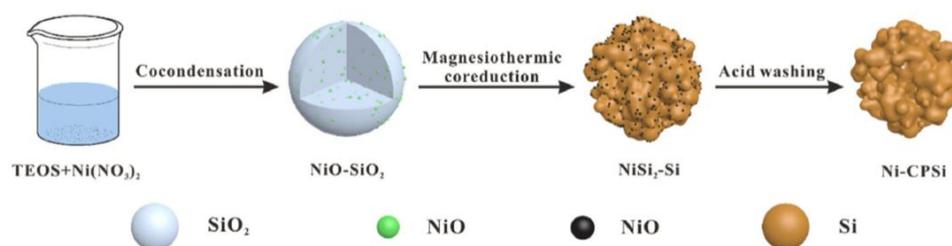
Fig. 2. Schematic diagram of the synthesis of Ni-CPSi [14].

Compared with pure silicon, Ni-CPSi demonstrated significant performance improvements. Microscopic analysis revealed that pure silicon particles aggregated into dense clusters due to excessive thermal effects during synthesis, whereas Ni-CPSi maintained a uniform porous architecture with reduced pore volume (0.3 cm³/g vs. 0.5 cm³/g for pure Si), effectively minimizing undesirable side reactions. Structural characterization confirmed lattice contraction in Ni-CPSi and increased crystallinity, supported by weakened amorphous phase signals. Electrical conductivity improved from 1.18×10^{-5} S/cm (pure silicon) to 8.75×10^{-3} S/cm (Ni-CPSi), consistent with reduced charge-transfer resistance observed in electrochemical impedance spectra. These enhancements contributed to an initial Coulombic efficiency of 83.59% (compared with 69.13% for pure silicon) and a retained capacity of 904.5 mAh/g after 1,000 cycles at 4.2 A/g [14].

This study highlighted the effectiveness of nickel doping and pore engineering in optimizing silicon anode performance. However, unresolved challenges included environmental risks from surfactants and microcrack formation under high current densities. Future efforts were suggested to explore bio-inspired templates for eco-friendly synthesis and pre-lithiation techniques to further improve initial efficiency. Such advancements were deemed critical for advancing silicon-based anodes toward practical applications in high-energy-density lithium-ion batteries.

3.3. Nano-Metal oxides coating

In the development of anode materials for lithium-ion batteries, designing nano-metal oxide coatings with enhanced electrochemical performance has been a critical strategy to improve energy density. This study successfully fabricated a three-dimensional porous carbon-supported zinc oxide/silicon composite coating through hydrothermal synthesis and high-temperature annealing, as illustrated in Fig 3. The synthesis procedure involved sequential dissolution of zinc acetate dihydrate, cetyltrimethylammonium bromide, sodium hydroxide, and ethylenediamine in anhydrous ethanol. A mixture of silicon dioxide and porous carbon powders was then introduced into the solution, followed by hydrothermal treatment at 180°C for 8 hours to form precursors. Subsequent ammonia etching and annealing at 500 °C under argon atmosphere produced a composite structure where zinc oxide nanorods and silicon nanoparticles were uniformly embedded within the porous carbon matrix. The hierarchical pore network and spatial distribution of components demonstrated that the porous carbon

matrix not only served as a conductive framework but also provided buffer zones to accommodate volume expansion, thereby enhancing structural stability.

Fig. 3 schematic illustration for the synthesis procedures of ZnO/Si/porous-carbon (ZSPC) composite powders. [15]

Electrochemical evaluations revealed that the composite coating retained a reversible capacity of 934 milliampere-hours per gram after 300 cycles at a 0.2 C-rate, significantly outperforming pure zinc oxide (240 milliampere-hours per gram) and zinc oxide/porous carbon (453 milliampere-hours per gram). This performance enhancement stemmed from synergistic interactions among components: the high electrical conductivity of porous carbon accelerated charge transfer, the three-dimensional architecture of zinc oxide nanorods suppressed electrode pulverization, and silicon nanoparticles contributed additional capacity via high lithium-ion adsorption. The initial Coulombic efficiency of 63% was attributed to irreversible solid electrolyte interphase layer formation, while subsequent cycles-maintained efficiencies above 97%. Notably, the material exhibited a capacity retention of 547 milliampere-hours per gram after 300 cycles at a high 2 C-rate, confirming its suitability for high-load applications.

Despite these advancements, practical implementation faced challenges. The environmental toxicity of cetyltrimethylammonium bromide used in hydrothermal synthesis and structural degradation risks under high current densities—such as microcrack formation caused by zinc oxide expansion—required resolution. Future efforts should prioritize eco-friendly solvent alternatives, strengthen chemical bonding at silicon-carbon interfaces, and employ in situ characterization techniques to monitor dynamic structural evolution during cycling. These improvements are essential to advance the industrial adoption of this composite coating in next-generation high-performance batteries.

4. Summary and suggestions

Silicon-based anode materials with nano-coatings can be categorized into three types: nano-carbon coatings, nano-metal coatings, and nano-metal oxide coatings. Each type enhances battery performance through distinct methods while facing unique challenges and opportunities for improvement. The detail showed in Table 1.

Nano-carbon coatings are typically synthesized using methods like chemical vapor deposition, thermal decomposition, or sol-gel processes. For example, mixing silicon particles with graphene and heat-treating them under inert gas forms a carbon-encapsulated structure. These coatings improve battery cycle life due to their high conductivity, which speeds up charge transfer, and their ability to buffer silicon's volume expansion during charging. However, under rapid charging conditions, the coating structure may collapse, and the weak bonding between the carbon layer and silicon particles can lead to peeling. Additionally, some solvents used in synthesis pose environmental risks. Future efforts could focus on eco-friendly solvent alternatives, chemical bonding techniques to strengthen interfaces, and scalable production methods like continuous chemical vapor deposition.

As for nano-metal coatings, such as those made from nickel or copper, are often prepared via electroplating or high-temperature reduction. These coatings enhance mechanical stability and conductivity while suppressing lithium dendrite growth, reducing overheating risks. For instance, nickel-based coatings significantly extend battery lifespan. However, the process often involves toxic surfactants, and raw metal materials are costly. Under high-stress conditions, micro-cracks may form in the coating, degrading performance. Solutions include using bio-templates to replace harmful chemicals, testing low-cost metals like iron, and employing real-time monitoring to track structural changes and optimize bonding.

Nano-metal oxide coatings, like titanium oxide or zinc oxide, are built using sol-gel methods or atomic layer deposition. These coatings act as physical barriers to mitigate silicon's volume expansion and reduce side reactions. For example, zinc oxide combined with porous carbon shows stable electrochemical performance. However, their synthesis is complex and expensive, and long-term cycling may cause interface delamination. Simplifying steps—such as developing one-step sol-gel methods—or replacing costly equipment could lower production costs. Strengthening adhesion between the oxide layer and silicon, or adding self-healing properties to repair cracks, could further boost durability.

Table. 1 Comparison of various coating modification on Si anodes

Type	advantages	disadvantages
Nano-Carbon coating	-high conductivity -Enhanced cycling stability	-risk at interface -Use of toxic solvents
Nano-Metal coating	-Enhance mechanical stability -Enhanced electrical conductivity -High retained capacity	-High cost of metal precursors and complex synthesis processes -micro-crack risk
Nano-metal oxide coating	-Retain volume expansion -Reduce side action -Compatibility with scalable methods	-Potential interfacial delamination during long-term cycling -Expensive for process

5. Conclusion

This study systematically analyzes the mechanisms and optimization potential of three types of nano-coatings (nano-carbon, nano-metal, and nano-metal oxide) for silicon-based anodes, with the following key findings:

(1) Nano-coating technologies significantly enhance the performance of silicon-based anodes through distinct approaches. Nano-carbon coatings improve charge transfer efficiency with their high conductivity while buffering silicon's volume expansion. Nano-metal coatings extend battery lifespan by enhancing structural stability and suppressing lithium dendrite growth. Nano-metal oxide coatings act as physical barriers to reduce side reactions. However, challenges such as weak interfacial bonding, high production costs, and environmental concerns remain unresolved for all three types.

(2) The preparation methods for these coatings vary in focus. Nano-carbon coatings are typically formed via chemical vapor deposition or sol-gel processes to create encapsulated structures. Nano-metal coatings rely on electroplating or high-temperature reduction to build protective metal layers. Nano-metal oxide coatings are synthesized using atomic layer deposition or hydrothermal reactions to generate oxide barriers. These methodological differences directly influence the coatings' performance and application scenarios.

(3) While all coatings contribute to multi-dimensional electrode optimization, further breakthroughs are needed. For example, nano-carbon coatings require improved structural stability

under high-current conditions, nano-metal coatings need cost-effective synthesis routes, and nano-metal oxide coatings demand simplified fabrication steps.

By continuously refining coating technologies, such as developing eco-friendly synthesis methods, strengthening interfacial adhesion, and advancing scalable production-the practical application of silicon-based anodes will accelerate. These advancements will not only enhance lithium-ion battery charging speeds and cycle life but also promote the widespread adoption of electric vehicles and renewable energy storage systems, providing robust support for global sustainable energy transitions.

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