The Impact of Silicon Anode Morphology in Lithium Batteries on Energy Storage Performance

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Abstract. With the rapid development of renewable energy, lithium-ion batteries have garnered significant attention. The anode material is one of the key factors determining the performance of lithium-ion batteries. Silicon anodes, due to their exceptionally high specific capacity and abundant reserves, are widely regarded as a promising alternative anode material. However, silicon anodes currently face challenges such as volume expansion and unstable SEI films, which lead to reduced cycling stability. This paper summarizes the improvements in the electrochemical performance of silicon anodes through nano structuring, including various preparation methods and the effects of materials of different dimensions on cycling stability. Research has found that nanomaterials of different dimensions can mitigate volume expansion to some extent, shorten lithium-ion diffusion paths, and enhance the conductivity of silicon anodes. The significance of this paper lies in providing a theoretical basis and research direction for the further development of higher-performance silicon anode materials, thereby advancing the progress of batteries and renewable energy.

Keywords: Sodium-ion batteries; Silicon anodes; Material morphologyr.

1. Introduction

To address environmental pollution, reduce carbon emissions, and curb greenhouse gas emissions, the role of renewable energy in the global energy structure has steadily increased in recent years. Traditional diesel vehicles are being phased out, and electric vehicles are becoming mainstream. As the driving component of electric vehicles, batteries directly determine their performance. Consumers seek affordable, high-performance electric vehicles, necessitating batteries with high energy density, stable cycling, and excellent safety.

Currently, lithium-ion batteries dominate the electric vehicle battery market due to their high energy density and long cycle life. A lithium-ion battery consists of three main components: the cathode, anode, and electrolyte, with the anode being a critical determinant of battery performance. Graphite, as a highly commercialized anode material, has been widely used, but its theoretical specific capacity (372 mAh/g) [1] no longer meets market demands, prompting the search for higher-performance materials.

Silicon anodes, with a specific capacity of 4200 mAh/g—approximately ten times that of traditional graphite anodes—and abundant natural reserves, are considered the most promising alternative for lithium-ion battery anodes. However, silicon anodes still face two major issues: severe structural deformation caused by volume expansion and capacity degradation due to unstable SEI films, which affect cycle life [2]. To address these challenges, researchers have employed various methods, including nano structuring silicon anodes to alter their morphology and properties. Different morphologies influence lithium-ion transport and battery cycle life. Studies show that nano-silicon materials can effectively alleviate volume expansion and improve electrochemical performance, optimizing battery parameters [3]. This paper analyzes the impact of known silicon anode morphologies on lithium-ion battery performance, focusing on the application of nano-silicon anodes and discussing the effects of different dimensional nanostructures.

2. Morphologies of Silicon Anode Materials

The working principle of silicon anodes involves alloying reactions with lithium, where charging and discharging correspond to lithiation and delithiation, respectively. During charging, lithium ions embed into the silicon electrode structure, forming lithium-silicon alloys, eventually crystallizing at full lithiation. During discharging, the lithium-silicon alloy decomposes into lithium and silicon ions but does not fully revert to the initial silicon state, instead forming a porous amorphous silicon structure. The lithiation and delithiation processes cause significant volume expansion (~300%), leading to electrode material pulverization, continuous SEI film rupture and regeneration, and reduced cycling performance [4]. Traditional pure silicon anodes face two major challenges: volume expansion and poor cycling stability due to unstable SEI films. Additionally, silicon's poor conductivity as a semiconductor necessitates conductive additives to achieve ideal performance.

Nanostructuring involves processing materials into nanomaterials, defined as materials with at least one dimension between 1–100 nanometers. Nanomaterials exhibit unique properties due to effects such as volume effects (altering grain properties by breaking periodic boundary conditions), surface effects (changing properties as the ratio of surface atoms to total atoms increases), and quantum size effects (discrete energy levels at small grain sizes). Nanomaterials also exhibit high hardness, plasticity, specific heat coefficients, thermal expansion coefficients, and conductivity [5]. Silicon anode nano structuring can mitigate volume expansion, improve conductivity, and shorten lithium-ion diffusion paths, enhancing rate performance. Different dimensional nano-silicon anodes address these issues by altering electrochemical and thermodynamic properties.

2.1. Nanostructured silicon anode materials of different dimensions

2.1.1. 0D Nano-Silicon Anodes: Silicon Nanoparticles

The preparation methods for zero-dimensional nano-silicon include chemical synthesis, laser ablation, and plasma-assisted synthesis, each of which endows the material with distinct advantages. For example:

As show in Fig.1, zero-dimensional silicon nanoparticles directly generated by laser ablation methods can help the anode to maintain a high performance.

However, these methods share common drawbacks: the preparation costs are generally high, the required equipment and materials are expensive, the preparation processes are complex, and the conditions are stringent.

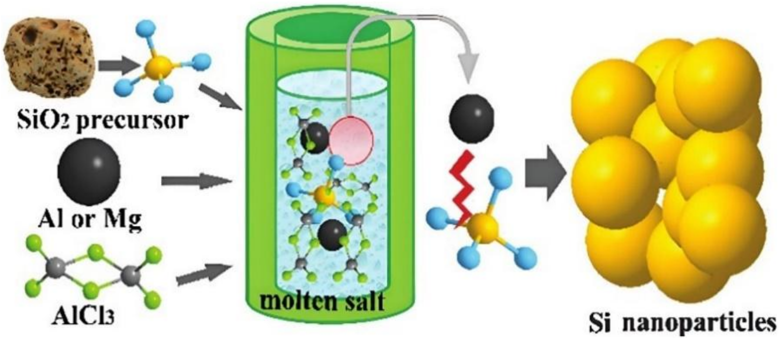

Fig 1. The preparation process of nano-silicon anodes [6].

Silicon nanoparticles, with diameters ranging from 1 to 100 nm, can improve conductivity and alleviate stress caused by volume expansion. However, they face challenges such as localized expansion damaging electrode structures. Coating conductive materials, such as carbon layers, can suppress side reactions [7].

2.1.2. 1D Nano-Silicon Anodes: Silicon-Carbon Nanocomposite Fibers

As show in Fig.2, the methods for preparing one-dimensional nano-silicon can generally be divided into chemical synthesis and physical synthesis. Vapor deposition is mentioned in both synthesis approaches:

Chemical vapor deposition (CVD) requires the use of metal catalysts to guide the growth of silicon nanowires from gas-phase precursors under high-temperature conditions. Physical vapor deposition (PVD) uses laser ablation to bombard silicon targets, causing silicon nanowires to deposit on substrates. Prepared via electrostatic spinning, these fibers combine high capacity and cycling stability but face commercialization hurdles due to complex processes and potential fiber breakage.

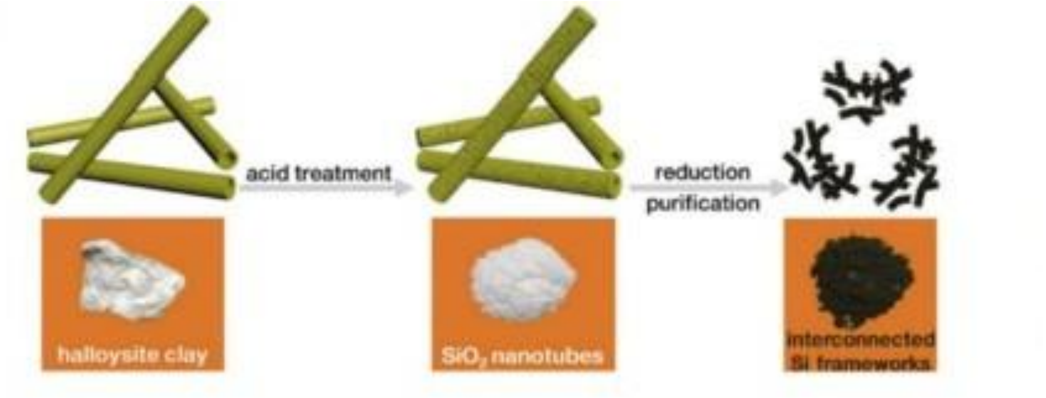

Fig 2. The preparation process of nano-silicon anodes [8].

2.1.3. 2D Nano-Silicon Anodes: Silicon Nanofilms

As show in Fig. 3, the synthesis methods for two-dimensional nano-silicon primarily rely on exfoliation techniques, where different materials are exfoliated using various methods, such as ultrasonic exfoliation.

These films, woven from silicon nanotubes, require stringent preparation conditions and may not fully address volume expansion. Adding materials like carbon nanotubes can enhance performance by providing structural support.

Fig 3. The preparation process of nano-silicon anodes [9].

2.1.4. 3D Nano-Silicon Anodes: Porous Nano-Silicon/Graphene

With advancements in technology, three-dimensional nano-silicon can now be prepared using 3D printing. Traditionally, the most mainstream preparation method involves template-based casting: Nano casting uses mesoporous silica as a template, achieving a capacity retention of 92% after 100 cycles [10].

Polymer templating employs polystyrene microspheres as templates, followed by chemical vapor deposition of silicon and calcination to obtain three-dimensional nano-silicon materials. This structure offers high cycling stability and energy density, with a high-capacity retention rate, but is susceptible to localized stress [11].

3. Recommendations and Future Perspectives

Silicon anodes' high capacity and abundance make them the most promising graphite alternative. Current research focuses on nano structuring to enhance performance, but high preparation costs hinder commercialization. Future efforts should prioritize cost reduction, process optimization, and exploring novel composite materials. Leveraging AI to optimize electrode-electrolyte combinations or develop advanced thermal monitoring systems could accelerate progress.

The future development direction of silicon anodes primarily focuses on the modification of its material properties or the preparation of composite materials. Nano structuring and porous architecture can effectively mitigate the volume expansion issue, with porous structures providing reserved expansion space while also enhancing electrical conductivity. The fabrication of silicon composites with other metals can help counteract the negative effects of silicon anodes or further improve their existing advantageous performance.

Cost control in preparation methods is essential, requiring optimization of common synthesis techniques such as chemical vapor deposition (CVD) to refine their processes, as well as the development of recycling technologies tailored for silicon anodes with inherently short cycle lives, thereby reducing overall costs.

Additionally, advancements in extending cycle life and fast-charging capabilities must be pursued, while the safety and stability of batteries also need further reinforcement. The continuous evolution of silicon anode technology will depend on innovations in material design, scalable manufacturing processes, and systematic improvements in electrochemical performance to meet the demands of next-generation energy storage applications.

4. Conclusion

Silicon's high capacity and reserves position it as the best graphite anode alternative. Nano structuring addresses volume expansion and SEI instability while improving conductivity, but commercialization remains challenging due to high costs. Future research should focus on cost-effective preparation techniques, novel composites, and AI-assisted development to advance silicon anode batteries with the advancement of technology and the increasing market demand, graphene anodes are gradually becoming obsolete, and silicon is emerging as the most mainstream anode material for lithium-ion batteries. This paper systematically investigates silicon anodes in lithium-ion batteries and finds that the primary challenges currently faced by silicon anodes are volume expansion and unstable solid electrolyte interphase (SEI) film formation. Nano structuring can modify the properties of traditional silicon anodes, thereby optimizing their performance, addressing issues related to volume expansion and SEI film instability, while also providing additional benefits such as shortening lithium-ion diffusion pathways and enhancing electrical conductivity.

Different morphologies of nanostructured silicon anodes exhibit distinct characteristics. Zero-dimensional (0D) nanostructured silicon anodes effectively mitigate volume expansion while providing a large specific surface area, reducing diffusion distances, and improving rate capability. One-dimensional (1D) silicon nanowires or nanotubes offer a more stable structure, ensuring that the material does not fracture during radial expansion while delivering long cycle life. Two-dimensional (2D) thin-film nanostructures, due to their minimal thickness, can tightly bond with other substrates to form multilayered architectures, enabling the electrode to possess multiple desirable properties simultaneously. Three-dimensional (3D) porous nanostructured silicon provides high porosity, accommodating volume expansion and maintaining electrode structural stability, while also enabling high active material loading, thereby enhancing battery energy density.

As a result, nano structuring is considered the most promising research direction for optimizing traditional silicon anodes, as it not only resolves existing issues but also further improves battery performance. Therefore, future research should focus on refining the preparation processes based on existing nanostructured silicon anode studies, reducing costs, and lowering production barriers to facilitate large-scale manufacturing as soon as possible. This will accelerate the commercialization of nanostructured silicon anode materials and enable their rapid deployment in practical applications.

This paper summarizes current research achievements and challenges in nanostructured silicon anodes, providing a valuable reference for subsequent studies and offering guidance for future research directions. It aims to promote further advancements in this field and contribute to the development of next-generation high-performance lithium-ion batteries.

References

[1] Zhao Ze. Applications of Nanotechnology: Lithium-Ion Based Batteries in Electric Vehicles. Engineering and Technology, 2023, 23(34): 83–90.

[2] Benning Svenja, Wei Chang. Direct Observation of SEI Formation and Lithiation in Thin-Film Silicon Electrodes via in Situ Electrochemical Atomic Force Microscopy. ACS Applied Energy Materials, 2019,44(23): 23345.

[3] Li Zhong, Ju Zhi, Li Jie, et al. Prelitigation of Silicon/Graphite Composite Anodes for Lithium-Ion Batteries. Advanced Materials, 2017, 45(32):34-45.

[4] Obrovac Meers, Ning Meng, Wu Zhi, et al. Fluoroethylene Carbonate as an Additive for Silicon-Based Lithium-Ion Batteries. Journal of The Electrochemical Society, 2014, 45(34): 56-64.

[5] Bruce Persa, Gao Ling, Scrosati Bersd, et al. Nanomaterials for Rechargeable Lithium Batteries. Angewandte Chemie, 2008,47(16): 2930–2946.

[6] Huang Pi, Zu Chang, Zhao Peng, et al. Research Status and Development of High-Capacity Silicon-Based Anode Materials for Lithium-Ion Batteries. Carbon Techniques, 2020, 23(3): 26-35.

[7] Li, W. Properties of Nanomaterials. Modern Chemical Industry,1999, 23(45): 36-42.

[8] Han Ming, Ying Ming, Lin Chen, et al.A low temperature molten salt process for aluminothermic reduction of silicon oxides to crystalline Si for Li-ion batteries.Energy & Environmental Science Ees, 2015,11(4): 234555.

[9] Shi Biao, Li Yuxi, Yi Hua, et al. Short-term load forecasting based on modified particle swarm optimizer and fuzzy neural network model. Systems Engineering-Theory and Practice, 2010, 30(1): 158-160.

[10] Gao Chan, Cao Jian, Wu Mingle, et al. Study on the Cycling Stability of Silicon Anodes in Lithium-Ion Batteries. Harbin Institute of Technology, 2011, 23(49): 29-34.

[11] Ren Yi, Xiang Ling, Yin Xi, et al. Ultrathin Si Nanosheets Dispersed in Graphene Matrix Enable Stable Interface and High-Rate Capability of Anode for Lithium-ion Batteries. Advanced Functional Materials, 2022, 32(16): 235445.