

Current Status and Development Potential of Nanomaterials in Lithium-Ion Batteries: Focus on Anode and Cathode Modification Strategies

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Abstract:

This paper provides a systematic review of the current applications and development potential of nanomaterials in lithium-ion batteries. Addressing challenges such as volume expansion, particle pulverisation, and unstable films in silicon-based anode materials, it summarises strategies including nanostructure design, composite modification, and novel binders to enhance cycling stability and conductivity. For issues like voltage decay, capacity reduction, and transition metal leaching in lithium-rich manganese cathodes, it analyses the efficacy of nanomodification methods—such as constructing multi-level conductive networks—in improving electron conduction and structural stability. Research indicates that nanomaterials, through their unique size effects, high specific surface area, and interfacial properties, significantly enhance the energy density, rate performance, and safety of lithium batteries. This provides crucial theoretical foundations and technical pathways for developing next-generation lithium batteries with high-energy-density. Future research should further focus on the large-scale preparation of nanomaterials, cost control, and their interface with electrolytes. These efforts will help advance practical applications in energy.

Keywords: Nanomaterials; silicon-based anodes; lithium-rich manganese cathodes; nanostructure design; multi-level conductive networks.

1. Introduction

With the rapid expansion of the global new energy vehicle industry, lithium-ion batteries face multiple

performance bottlenecks as the core power source, including energy density, fast-charging capability, and safety. Traditional graphite anodes possess limited theoretical capacity ($372 \text{ mAh}\cdot\text{g}^{-1}$), struggling to

meet the demands of next-generation high-energy-density batteries. Nanomaterials demonstrate significant potential for enhancing battery performance due to their unique quantum size effects, high specific surface area, and tunable interfacial properties. In recent years, silicon-based anode materials have emerged as a research focus because of their exceptionally high theoretical specific capacity (3579–4200 mAh·g⁻¹) and favourable operating potential (approximately 0.4 V vs. Li⁺/Li). However, the significant volume expansion (approximately 300%) occurring during charge-discharge cycles leads to issues such as particle pulverisation, electrode structural collapse, and SEI film instability, severely hindering their commercial application. Concurrently, lithium-rich manganese cathode materials (e.g., Li_{1.2}Mn_{0.54}Ni_{0.13}Co_{0.13}O₂) exhibit high specific capacity (>250 mAh·g⁻¹) and operating voltage (~4.8 V), yet face challenges including voltage decay, capacity decline, and transition metal leaching. This paper systematically reviews the current application status of nanomaterials in lithium batteries, focusing on modification strategies for nano-silicon-based anodes and nano-composite cathodes. It aims to provide theoretical foundations and technical pathways for overcoming current battery performance bottlenecks.

2. Properties of Nanomaterials

Nanomaterials exhibit significant advantages in electrochemical energy storage due to their size effects, high specific surface area, and interfacial characteristics. Their quantum confinement effect enhances the electron transport and ion diffusion capabilities of electrode materials, while the high specific surface area provides more active sites for electrochemical reactions, significantly improving electrode specific capacity and reaction kinetics. Furthermore, the interfacial effects of nanomaterials optimise electrode/electrolyte interactions, promoting stable SEI film formation, inhibiting lithium dendrite growth, and increasing battery safety and cycling stability. These properties render nanomaterials indispensable for improving lithium battery energy density, rate performance, and lifespan.

3. Modification Studies on Nanoscale Silicon-Based Anode Materials

Silicon-based materials possess a theoretical specific capacity far exceeding that of existing materials and are regarded as a key candidate system for developing advanced high-energy-density lithium-ion battery anodes (3579–4200 mAh g⁻¹) and suitable operating potential (approximately 0.4 V vs. Li⁺/Li)[1]. However, the significant

volume change (approximately 300%) that occurs during the lithiation/delithiation process leads to issues such as particle fragmentation, electrode structure damage, and instability of the solid electrolyte interphase (SEI) film, severely hindering its commercialisation. In recent years, researchers have significantly improved the electrochemical performance of silicon-based anodes through strategies such as nanostructure design, composite modification, and the development of new binders.

3.1 Nanostructure and Pore Design: Alleviating Volume Expansion Issues

Size effects play a crucial role in improving the cycling stability of silicon anodes. Studies have shown that when silicon particle size is reduced to the nanoscale, its resistance to fragmentation is significantly enhanced. Liu et al. observed via in situ transmission electron microscopy that silicon particles smaller than 150 nm do not develop cracks or fractures during lithiation [2]. Silicon nanoparticles with a particle size below 50 nanometres were successfully synthesised by Fang et al. using a ball-milling-assisted low-temperature aluminothermic reduction method. This material retained a reversible capacity of 804 milliampere-hours after 400 cycles at a current density of 1 ampere per gram. This demonstrates significantly superior performance compared to conventional micron-scale silicon materials, highlighting the advantages of nanomaterials.

In recent years, multi-level pore structure design has garnered attention for its potential to enhance electrode performance. Wang et al. synthesised monodisperse porous silicon nanospheres (MPS) featuring uniformly distributed pores with diameters around 200 nanometres [3]. This structure reduces volumetric expansion during charge-discharge cycles while improving electrolyte permeability and lithium-ion migration rates. Electrochemical testing indicates MPS exhibits outstanding cycling durability, retaining a high reversible specific capacity of 1500 mAh g⁻¹ after 500 cycles at a C/2 rate. Furthermore, the ant-nest-like microporous silicon (AMPSi) studied by the An team possesses a three-dimensional interconnected pore network. This structure further enhances the material's mechanical stability, delivering significantly improved electrochemical performance compared to conventional materials.

3.2 Composite Strategies: Enhancing Conductivity and SEI Stability

Composite strategies combine silicon with carbon materials, metal oxides, or MXene to effectively address the poor conductivity and unstable SEI of silicon-based materials.

In carbon-based composites, core-shell structures (e.g., m-RWSi@PMMA-C) enhance electronic conductivity efficiency while suppressing silicon particle fragmentation through carbon layer coating. The eggshell structure (e.g., Si@C@void@C) reserves a cavity between the core and shell, providing additional space for volume expansion, enabling the material to maintain a high capacity (1598 mAh g⁻¹) over 1500 cycles [4]. In non-carbon-based composites, Al₂O₃ coating layers effectively stabilise the SEI film, while MXene materials (e.g., Ti₃C₂Tx) demonstrate significant potential for improving silicon anode performance due to their unique two-dimensional structure and excellent conductivity.

3.3 Binder Optimization: Maintaining Electrode Structural Integrity

Binder optimisation is crucial for maintaining electrode structural integrity. Traditional PVDF binders struggle to accommodate silicon's large volume changes due to weak interactions with silicon particles[5]. Novel cross-linked polymer binders (e.g., PAA-UPy) form a three-dimensional network structure, enhancing adhesion strength while also exhibiting self-healing capabilities. Studies show that Si/C anodes using PAA-UPy binder maintain a capacity retention of 85% after 110 cycles at 0.5C. Another cross-linked binder, SHA, formed by the physical interweaving of hyaluronic acid and soluble soybean polysaccharides, enables the electrode to keep a capacity of 1252 mAh g⁻¹ after 250 cycles with a high current of 2 A g⁻¹.

4. Performance enhancement of nano-composite cathode materials

4.1 Issues and Challenges with Lithium-Rich Manganese-Based Cathode Materials

The lithium-rich manganese layered oxide cathode material (Li_{1.2}Mn_{0.54}Ni_{0.13}Co_{0.13}O₂, LMNCO) has garnered significant attention because of its high specific capacity (>250 mAh g⁻¹) and high functioning voltage (~4.8 V), positioning it as an ideal candidate for advanced high-energy-density lithium-ion batteries[6]. However, this kind of material faces significant challenges in practical applications: voltage decay, capacity degradation, and transition metal dissolution during cycling severely impede its commercialisation. These issues primarily stem from the material's structural instability and reactions occurring at the electrode/electrolyte interface are side reactions. Particularly under high-voltage operating conditions, the loss of lattice oxygen and phase transformations lead to irreversible structural changes, subsequently causing a

decline in electrochemical performance. Furthermore, low electrical conductivity and ion diffusion rates constrain its rate performance. To address these issues, researchers have significantly enhanced the electrochemical performance of LMNCO cathodes by constructing nanoscale conductive networks and material synthesis methods.

4.2 Multi-level Conductive Networks Enhance Cathode Material Performance

Latif et al. innovatively constructed a "point-line-surface" multi-level conductive network comprising CNTs (lines), GNRs (surfaces) and GQDs (points), significantly enhancing the electronic conductivity of LMNCO cathode materials while suppressing side reactions. Atomic-level uniform mixing was achieved via the nitrate co-precipitation method, with GNRs and GQDs prepared through low-cost, scalable techniques[3]. This architecture elevated the material's crystalline order, yielding a (003)/(104) peak intensity ratio >1.2 and low cation mixing. Electrochemical performance markedly improved: initial discharge capacity reached 261.78 mAh g⁻¹ at 0.2C, with 87% capacity retention after 150 cycles at 1C (compared to 63.24% for the raw material)[4]. The internal resistance decreased from 7.2Ω to 5.1Ω, indicating enhanced reaction kinetics[10]. Adjusting the Mn oxidation state and carbon coating further strengthened structural and thermal stability. Transmission electron microscopy (TEM) revealed uniform elemental distribution without phase separation, ensuring consistent performance.

5. Conclusion

This study systematically analyses the application potential and current development status of nanomaterials in lithium batteries. For anodes, volume expansion issues in silicon-based materials have been significantly mitigated through nanostructure design, composite modifications, and novel binder development, thereby enhancing cycling stability and conductivity. For cathodes, constructing multi-level conductive networks has effectively enhanced electron conduction and structural stability in lithium-rich manganese-based materials, suppressing voltage decay and capacity decline. Findings indicate that incorporating nanomaterials not only elevates battery energy density and rate capability but also offers viable pathways for thermal management, safety enhancement, and lifespan extension in practical applications. Future research should further focus on the large-scale preparation of nanomaterials, cost control, and their interface with electrolytes to advance their commercial application in high-performance lithium batteries.

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