Enhancing the performance of lithium-ion batteries by different types of nanomaterials

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Abstract. This research analyzes the application performance of nanomaterials in lithium-ion batteries (LIBs). Composite materials made of silicon and carbon have shown promise as a way to greatly improve the performance of LIBs. Silicon offers substantial improvements over traditional graphite anodes. The significant volume expansion of silicon during cycles of charge and discharge, however, brings several difficulties, including electrode deterioration and mechanical stress. Advanced structural designs, including nanostructuring, hollow particles, and Si@C core-shell architectures, have been developed. These developments preserve high capacity and cycle stability while mitigating volume variations. In order to further increase the cycle life and specific capacity of silicon anodes, carbon-based materials like graphene and carbon nanotubes (CNTs) are essential for boosting the conductivity, flexibility, and structural integrity of silicon anodes. Despite these advancements, engineering challenges remain, particularly in terms of complex fabrication processes and cost-effective scalability. Future trends will focus on optimizing material design, improving manufacturing processes, and exploring new composite and coating technologies. These advancements could enable the nanomaterial to become a key component in LIBs, with improved capacity retention, safety, and manufacturability.

Keywords: lithium-ion batteries; nanomaterials; application.

1. Introduction

Compared to traditional batteries, lithium-ion batteries (LIBs) offer faster charging, extended lifespan, and higher power density, providing increased energy capacity in a more compact and lightweight form [1]. This makes them the preferred option for energy storage systems, electric cars, and portable electronics. However, despite the excellent characteristics of LIBs across various applications, predicting their lifespan under high-load and extreme usage conditions remains a significant challenge. Frequent fast charging extended high-speed driving, or continuous operation in autonomous driving scenarios can accelerate battery degradation. While silicon compounds are added to graphite anodes to enhance energy density, their high volumetric expansion worsens mechanical stability. Greater volume fluctuations during cycling due to a larger silicon content cause structural damage to the electrodes and an increase in internal resistance. Excessive expansion can trigger cell failure, threatening the overall structural integrity of the battery pack. In electric vehicles (EVs), the high cost is mainly attributed to the expensive battery packs and complex engineering, which present a barrier to their widespread adoption. Continued reductions in these costs are essential to improving the market acceptance of EVs. Therefore, traditional LIBs need to be improved.

The development of nanotechnology has created new opportunities for enhancing the performance of LIBs. It has enhanced energy density, reduced recharging times and extended cycle life. By introducing nanomaterials into different parts of LIBs, such as nanostructured fluids, nanocoating, anode and cathode, these have improved maximum battery capacity, cycle life, and safety. LIBs are also crucial in EVs and hybrid electric vehicles (HEVs) because they aid in overcoming the polluted environment, a key factor in the widespread adoption of electric mobility. In aerospace applications, LIBs have a big breakthrough. It offers advantages such as lightweight design, high specific energy, and stable performance across a wide temperature range, making them ideal for powering spacecraft and aviation systems. In the medical field, LIBs can be used as like pacemakers and neurological implants, where reliability, long life, and stable power output are essential for patient safety. LIBs are

essential to the development of these developing technologies because they provide long-lasting power with less frequent recharging for new industries like drones, robots, and energy storage systems.

This research will concentrate on the application of silicon and graphite in LIBs to improve energy density and cycling performance. While silicon's high capacity enhances battery potential, its significant volumetric expansion during cycling poses mechanical challenges, leading to structural degradation. By optimizing the balance between silicon and graphite in anodes, it aims to mitigate these expansion issues while improving electrode stability. This research explores how advanced materials like nanotubes, silicon, graphene, and metal oxides can enhance energy storage, ion flow, and charging efficiency, further extending LIBs performance under demanding conditions.

2. Silicon-based nanomaterials for LIBs

Commercial LIBs typically utilize graphite anodes and lithium metal oxides or lithium iron phosphate cathodes. Moreover, silicon is plentiful and ecologically benign in the Earth's crust, therefore expanding LIBs' gravimetric capacity might further reduce their actual cost per unit energy. Silicon experiences significant volume changes during lithiation and delithiation, leading to the formation of unstable surface electrolyte interphase (SEI) layers that result in irreversible capacity losses, pulverization, and reduced cycle efficiency. The electronic conductivity of Si is relatively low, lithium diffusion in materials is rather slow [1-3], which can severely limit its overall capacity and hinder rate performance.

2.1. Silicon nanoparticles

The second most abundant element on Earth, silicon has a high theoretical capacity and is compatible with existing manufacturing processes. Their small size helps prevent cracking during lithium insertion, improving cycling performance. However, there may be difficulties because of the large volume changes that occur during charge and discharge. The use of various binders can improve cycling performance. Polyacrylic acid (PAA) and alginate binders have shown significant improvements. Functional group modifications increase the mechanical strength and binder conductivity even more, increasing the specific capacity of silicon nanoparticle electrodes.

2.2. Silicon nanoparticles/porous carbon

Silicon nanoparticles integrated with porous carbon structures provide notable benefits for anodes in LIBs by effectively addressing the challenges posed by silicon's substantial volume fluctuations during cycling. The porous architecture of silicon nanoparticles allows for additional expansion space during lithiation, thereby enhancing cycling performance and mitigating the impact of volume changes. After 100 cycles at 0.2 C, the specific capacity was maintained at 2780 $mAh \cdot g^{-1}$, representing 99% retention of the initial cycle capacity [4]. Additionally, porous carbon composites facilitate lithium ion transport and accommodate the expansion of silicon.

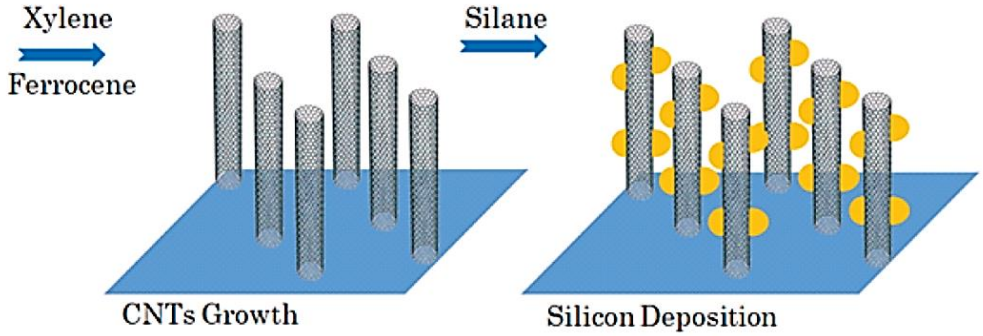

Fig. 1 Schematic of silicon/carbon nanotubes fabrication [5].

In one approach, silicon nanoparticles were deposited onto an aligned carbon nanotubes (CNTs) array substrate using a straightforward two-step chemical vapor deposition (CVD) method (Fig. 1),

resulting in a composite anode that achieves a capacity of 2000 mAh·g^{-1} with only 0.15% decay per cycle over 25 cycles [5, 6]. Another approach involved carbonizing porous silicon-poly(vinylidene fluoride) precursors to form a composite anode, achieving a notable specific capacity and demonstrating good stability after multiple cycles.

2.3. Hollow silicon and Si@C core-shell nanostructures

Hollow silicon and Si@C core-shell nanostructures significantly enhance the cycling performance of LIBs. Hollow silicon atoms initially deliver a high capacity and maintain good retention after many cycles, demonstrating excellent reversible capacity at elevated rates. The hollow structure facilitates rapid lithium diffusion and maintains structural stability despite SEI formation. Research has shown that hollow silicon particles treated with silver enhance electronic conductivity and cycling performance. Si@C core-shell structures demonstrate strong cycling performance, with the carbon and SiO_x layers in these structures aiding in stabilizing silicon and minimizing expansion, which contributes to enhanced performance.

2.4. Silicon nanoparticles/graphene composite

Silicon nanoparticles/graphene composites are highly promising for LIBs anodes, which can help accommodate silicon's volume changes during cycling. This integration enhances both the cycling performance and overall stability of the electrode. One approach involved creating silicon/graphene composites by filtering silicon/graphene oxide solutions, followed by a reduction process, which yielded a reversible specific capacity of 1500 mAh·g^{-1} [7]. Another approach utilized electrostatic self-assembly to uniformly coat silicon nanoparticles with graphene, resulting in a reversible steady capacity of 1205 mAh·g^{-1} [8]. Additionally, combining silicon nanoparticles with CNTs further improved electrode performance by increasing conductivity and minimizing degradation during cycling. The dispersion of silicon nanoparticles in graphene composites has been optimized through the use of molecular dynamic simulation. Performance has been improved by avoidance of aggregation decreases with smaller nanoparticle sizes. The unique morphology of the silicon nanoparticles in LIBs offers a stable cycling performance, resulting in a silicon/graphene composite with specific capacities of 1400 mAh·g^{-1} [9].

2.5. Nanowires and nanotubes

Silicon nanotubes offer high capacity and improved cycling performance for LIBs anodes due to their expandable tubular structure. While they provide excellent stability and capacity retention, their high cost and low volumetric density pose challenges. Advances in coatings and fabrication methods are ongoing to enhance their practicality for commercial use. Carbon-coated silicon nanotubes (SiNTs) have been developed through reductive decomposition, showing strong initial discharge capacity and coulombic efficiency. After extended cycling, the capacity retention remained high, attributed to the particular tubular structure of silicon. Shorter tubes with thinner walls and a smaller radius are more likely to have longer cycle lives. Silicon nanowires can accommodate volume changes and enhance cycling stability. Various coatings, such as carbon or copper, have been used to addressing issues like low initial efficiency and capacity loss.

2.6. Silicon thin films

Silicon thin films have shown great potential as anodes for LIBs, offering high capacity and long cycle life. Amorphous Si films and thin films with proper treatments to half-cells and full cells. These advancements highlight the effectiveness of silicon thin films in overcoming mechanical degradation issues and offer a viable alternative to traditional graphite anodes. Amorphous silicon films exhibit a reversible specific capacity over multiple cycles, while silicon nanocrystals with nanoscale dimensions enhance performance by preventing bulk mechanical failure due to their smaller domain size, which is below the critical fracture size, and the absence of dislocations. In another study, P-doped (n-type) Si thin films with a thickness of 50 nm achieved a high specific capacity of around

2100 $mAh \cdot g^{-1}$ over an impressive number of cycles, satisfying the cycle life requirements for advanced electric vehicle batteries [10]. For Full cell ,6 μm thick Si thin films with a limited capacity of 1800 $mAh \cdot cm^{-2}$ per cycle demonstrated stable cycling performance and nearly 100% coulombic efficiency for up to 250 cycles.

Silicon thin-film electrodes degrade mechanically and electrochemically, with mechanical degradation resulting from substantial volume expansion during lithiation and delithiation, causing stress and cracks. Thinner films perform better, as they are further resilient to stress, delaying plastic deformation and cracking. For example, 250 nm amorphous Si films remained stable over 30 cycles, while 1 μm films endured steady capacity decay after 15 cycles [11]. Patterning thin films to allow for adequate stress relief by generating artificial cracks is an effective method to prevent further cracking. When the pattern size is below the critical crack spacing, additional cracking is minimized.

3. Carbon-based nanomaterials for LIBs anodes

Carbon-based nanomaterials are ideal candidates for anodes in LIBs because of their thermal stability, accessibility, and affordability. Comparisons between carbon-coated and uncoated anodes have shown that the carbon coating enhances performance by creating a thinner and denser SEI layer, measuring 60–150 nm, in contrast to the 450–980 nm layer observed on non-coated graphite. This enhancement leads to reduced electrolyte decomposition and contributes to improved overall battery performance.

3.1. CNTs and carbon nanofibers (CNFs)

CNTs are commonly utilized in LIBs anodes due to their remarkable mechanical strength, stability against chemicals, expansive surface area, and outstanding electrical conductivity. Their small diameter and high aspect ratio enable better lithium intercalation and de-intercalation. Nonetheless, CNTs frequently demonstrate high irreversible capacity and low coulombic efficiency, issues that can be alleviated using functionalization approaches like graphitization. Hybrid systems that combine CNTs with other nanomaterials, such as Fe_3O_4 or $CoFe_2O_4$ nanocrystals, have shown increased capacity, longer cycling life, and improved efficiency, making CNTs a promising choice for LIBs anodes.

CNFs are one-dimensional graphitized nanostructures used in LIBs anodes. CNFs are advantageous for LIBs due to their ability to facilitate faster lithium diffusion. This results from their lattice and surface defects, which promote quicker lithium intercalation and de-intercalation, thus enhancing battery efficiency. CNFs offer good conductivity and mechanical stability.

3.2. Graphene

Graphene is a highly regarded material for LIBs anodes owing to its exceptional electrical conductivity, charge transportation, structural adaptability, light weight, and expansive surface area. These properties significantly enhance the electrochemical properties of LIBs anodes, more active sites for the intercalation and de-intercalation of lithium ions are available on graphene's vast surface area. When graphene is combined with active metals or metal oxides, graphene helps minimize irreversible capacity loss during charge-discharge cycles, thereby prolonging the lifespan of anode electrodes.

For instance, researchers have synthesized disordered graphene sheets through methods like electron beam irradiation and pyrolysis, which create additional active sites from structural defects, leading to a high gravimetric capacity. Another study developed a high surface area graphite with few graphene layers, achieving a reversible capacity of up to 1200 mAh/g in initial cycles [12]. Even at high current densities, the material maintained strong capacity and demonstrated promising lifecycle durability.

4. Metal oxides for LIBs anodes

4.1. Iron oxides

Iron oxides, such as α-Fe_2O_3, γ-Fe_2O_3, and Fe_3O_4, present attractive options for anode materials in LIBs because of their natural abundance, cost-effectiveness, and non-toxic nature. Different nanostructures, including α-Fe_2O_3 hollow spheres, nanofibers, and Fe_3O_4 nanotube arrays, demonstrate excellent capacity retention and stability, making them suitable candidates for enhancing battery performance. For example, γ-Fe_2O_3 nanofibers, with a carbon coating, demonstrated a capacity of 1197 mA h g^{-1} at 10 A g^{-1} and a higher lithium diffusion coefficient compared to α-Fe_2O_3. α-Fe_2O_3 hollow spheres showed over 700 mA h g^{-1} capacity with excellent reversibility over 100 cycles, while α-Fe_2O_3 nanotubes achieved nearly 750 mA h g^{-1} [13], benefiting from a carbon coating that enhances stability and conductivity. The morphology and structural properties of iron oxides significantly impact their performance, with α-Fe_2O_3 hollow spheres maintaining capacity longer, suggesting a more durable structure for long-term use.

4.2. Cobalt oxides

Cobalt oxides are notable anode materials for LIBs due to their excellent redox properties, high theoretical capacity, and good capacity retention. They can be shaped into various nanoforms, such as nanosheets, nanowires, and porous structures, which accommodate significant volume changes. In addition, there are the synthesis of CoO octahedral nanocages and Co_3O_4 mesocrystal nanoplates, both of which demonstrate enhanced performance due to their unique structures. Additionally, innovative Co_3O_4 nanostructures have shown superior rate capability, further highlighting the potential of cobalt oxides in improving LIBs performance.

5. Other types materials for LIBs

5.1. Monoanion cathode materials

$LiCoO_2$ (LCO), which is employed in LIBs cathodes and is valued for its extended lifespan and low self-discharge rates, has drawbacks, including high cost, inadequate rate performance, and thermal instability brought on by exothermic interactions at the cathode. Nanostructuring lithium cobalt oxide (LCO) can enhance its performance by increasing specific surface area and reducing ion diffusion lengths. Hydrothermal processing and post-templating have been utilized to synthesize LCO nanoparticles. The use of LCO cathodes coated on stainless steel substrates can enhance electrolyte infiltration and reduce lithium ion diffusion paths, leading to improved performance.

High-temperature lithium cobalt oxide (HT-LCO) nanoparticles, ideally sized between 15 and 30 nm, also show promise for elevated temperature applications. Zehetmaier et al. synthesized HT-LCO nanocrystals with a high surface area and demonstrated capacities of ~100 mA h g^{-1} [14]. Liu et al. enhanced LCO's reversible capacity by doping with La and Al, achieving 190 mA h g^{-1} with 96% retention [15]. This improvement increased structural stability and reduced dissolution.

$LiMn_2O_4$ is a viable cathode material for LIBs for its low toxicity and affordability. It does, however, have capacity loss and stability issues, especially at elevated temperatures. Spinel-structured $LiMn_2O_4$ synthesized from $MnCO_3$ precursors demonstrates impressive capacities. Additionally, the development of a three-dimensional (3D) spinel $LiMn_2O_4$ electrode using manganese dioxide and Li_2CO_3 shows competitive capacity, attributed to shorter diffusion length and larger surface area.

$LiNiO_2$ (LNO) presents a difficulty with thermal stability despite offering cheap processing costs and high energy density. Advances in LNO research include doping to enhance performance. $Li[Ni_{0.45}Co_{0.1}Mn_{1.45}]O_4$, benefits from increased specific capacity and structural stability as a result of the nickel and manganese combination.

5.2. Polyanion cathode materials

Recent studies have focused on enhancing the performance of lithium iron phosphate ($LiFePO_4$) by exploring various structural modifications. For instance, Peng et al. reported that $LiFePO_4$ nanowires with a uniform carbon layer achieved specific capacities of 150 mA h/g at 1 C and 110 mA h/g at 30 C [16], compared to 130 mA h/g and 60 mA h/g for commercial $LiFePO_4$, respectively. This improvement in conductivity is linked to an enhanced lithium-ion diffusion coefficient. Furthermore, because of the high surface area of the graphene foam, binder-free $LiFePO_4$ facilitated on it shows a reversible capacity at increased speeds and maintains a high percentage of its capacity after several cycles. Furthermore, recent advancements in synthesizing LFP nanoplates have revealed improved rate capabilities compared to bulk LFP. In another area of research, doping lithium cobalt oxide (LCO) with La and Al has been found to significantly enhance reversible capacity and structural stability, which reduces cathode dissolution at high cutoff voltages. Lithium manganese phosphate ($LiMnPO_4$) is noted for its high energy and power density but faces challenges related to low conductivity and high processing costs. However, nanostructuring LMP has shown promise in mitigating these issues, leading to satisfactory cyclability in synthesized LMP nanoplates.

5.3. Electrolytes

Electrolyte materials for LIBs are typically categorized into solid polymer electrolytes (SPEs) and liquid electrolytes (LEs) [17]. Recent advancements in solid polymer electrolytes have demonstrated significant improvements in ionic conductivity and electrochemical performance. Zhao et al. incorporated $Li_{1.3}Al_{0.3}Ti_{1.7}(PO_4)_3$ (LATP) nanoparticles into polyethylene oxide lithium to create a solid composite electrolyte [18]. The addition of 5 wt% LATP nanoparticles enhanced ionic conductivity, demonstrating improved electrochemical performance. $Li_{1.4}Al_{0.4}Ti_{1.6}(PO_4)_3$ was used as a filler in PEO-based polymer electrolytes.

Within the domain of liquid electrolytes, cross-linked composite gel polymer electrolytes were made using methacrylate-functionalized mesoporous SiO_2 (MA-SiO_2) nanoparticles [19]. These nanoparticles provided efficient pathways for lithium ion transport through their inner-pore channels. The enhanced mass transport contributed to improved cycling performance, especially at high operating temperatures. Overall, these advancements illustrate how nanotechnology is advancing electrolytes by improving ionic conductivity, physical stability, and mass transport, thereby leading to better performance and safety in LIBs [20-22].

6. Perspectives

In LIBs, silicon nanoparticles encounter challenges stemming from substantial volume changes during charge and discharge, resulting in cracking and diminished cycling performance. To address this, advanced binders like PAA and alginate enhance the mechanical strength and conductivity of the electrodes, enhancing cycling stability and doubling the specific capacity. In contrast, the incorporation of porous structures into silicon nanoparticles allows for expansion, hence mitigating mechanical stress. Porous silicon anodes may sustain high capacity across several cycles, attaining a specific capacity that stays high after 100 cycles. Both approaches improve the performance of silicon-based anodes while successfully addressing the issues associated with volume change. Hollow silicon and Si@C core-shell nanostructures address the challenges of silicon's significant volume changes during cycling by maintaining structural stability and enhancing performance. Hollow silicon particles facilitate lithium diffusion and retain high capacity. Si@C core-shell structures stabilize silicon through carbon and SiO_x layers, maintaining better performance over many cycles. Silicon nanoparticles/graphene composites leverage graphene's conductivity and flexibility to accommodate silicon's volume changes. The integration of CNTs and molecular dynamics simulations optimize dispersion and performance, effectively addressing issues of volume expansion, stability, and performance degradation in silicon-based anodes. The development of silicon nanoparticles/porous carbon composites, silicon nanotubes, and silicon nanowires addresses key challenges in LIBs by

enhancing cycling performance and stability. Porous carbon composites improve lithium ion transport and accommodate silicon's expansion, with methods like carbonizing precursors. Silicon nanotubes, with their expandable tubular structure, provide high capacity and excellent stability, evidenced by an initial capacity of 3648 $mAh \cdot g^{-1}$ and 89% retention after 200 cycles [17]. Nanowires, grown through various techniques, accommodate volume changes and improve stability. They benefit from coatings like carbon and copper and optimized growth methods, which reduce crack formation and enhance cycling life. These advancements collectively address issues related to volume expansion, capacity retention, and overall anode performance. Silicon thin films improve LIBs anodes by mitigating mechanical and electrochemical degradation. Amorphous and nanoscale silicon films offer high capacity and long cycle life. Thinner silicon films generally perform better than thicker ones, handling stress more effectively and reducing cracking. Patterning thin films to create artificial cracks helps manage stress and enhances stability, addressing common issues of capacity loss and film degradation.

Various advancements in anode materials have significantly enhanced the performance of LIBs. Carbon coating reduces the thickness of the SEI layer from 450–980 nm to 60–150 nm, improving battery stability and performance. CNTs and CNFs address high irreversible capacity and low coulombic efficiency by enhancing lithium storage and electron transfer, with CNTs showing improved capacity and cycling life when combined with hybrid materials like Fe_3O_4. Graphene, characterized by its high electrical conductivity and large surface area, enhances electrochemical performance and improves capacity retention over multiple cycles [22]. Titanium-based nanomaterials, such as $Li_4Ti_5O_{12}$ and $Li_2Ti_3O_7$ composites, improve cycle stability and safety by maintaining a stable potential and preventing overcharging. Collectively, these innovations address key challenges in LIBs anodes, leading to substantial improvements in capacity, cycling life, and overall battery performance.

Monoanion materials like LCO have improved through nanostructuring and doping, achieving capacities up to 190 $mAh \cdot g^{-1}$ with notable stability. $LiMn_2O_4$ has been optimized for high-temperature applications, showing capacities of around 96.4 $mAh \cdot g^{-1}$ at 20 C, with three-dimensional spinel structures improving performance further. LNO benefits from doping to enhance its stability and specific capacity. In polyanion cathodes, $LiFePO_4$ nanowires with carbon layers and $LiFePO_4$ supported on graphene foam have improved specific capacities and cycle stability. $LiMnPO_4$ nanoplates have achieved capacities of 168 $mAh \cdot g^{-1}$, addressing previous conductivity issues. High nickel layered oxides exhibit enhanced rate performance and electrochemical kinetics, with materials reaching up to 123 $mAh \cdot g^{-1}$ at high C-rates. These advancements address challenges in capacity, stability, and rate performance, leading to notable improvements in LIBs efficiency and longevity. Electrolytes have notably enhanced performance, primarily through nanotechnology integration. For SPEs, incorporating LATP nanoparticles into polyethylene oxide lithium has significantly increased ionic conductivity. In liquid electrolytes, the use of methacrylate-functionalized mesoporous SiO_2 ($MA\text{-}SiO_2$) nanoparticles in composite gel polymer electrolytes has improved cycling performance and stability, particularly at higher temperatures. These advancements highlight how nanotechnology boosts ionic conductivity, enhances mass transport, and improves overall electrolyte performance and safety in LIBs.

7. Conclusion

Substantial volume changes during charge and discharge can result in cracking and reduced cycling performance. To address this, advanced binders like PAA and alginate improve the mechanical strength and conductivity of the electrodes, enhancing cycling stability and doubling the specific capacity. Alternatively, incorporating porous structures into silicon nanoparticles provides space for expansion, reducing mechanical stress. Porous silicon anodes can maintain high capacity over many cycles, with a specific capacity of 2780 $mAh \cdot g^{-1}$ sustained at 99% after 100 cycles. By introducing nanostructures, hollow designs, and Si@C core-shell structures, silicon-based anodes not

only increase capacity but also mitigate the issue of volume expansion during cycling. The incorporation of carbon coatings and graphene further improves conductivity and structural integrity, enabling silicon-carbon composites to achieve high capacity and lifespan. CNTs and CNFs address high irreversible capacity and low coulombic efficiency by enhancing lithium storage and electron transfer, with CNTs showing improved capacity and cycling life when combined with hybrid materials like Fe_3O_4. Graphene enhances electrochemical performance and improves capacity retention over multiple cycles. However, silicon-based materials face engineering challenges due to their significant volume expansion, which can lead to electrode failure. Nanostructured silicon particles, hollow designs, and carbon composites are used to reduce stress, but these require complex nanomanufacturing processes and surface modifications, leading to higher production costs. In comparison, carbon-based materials are easier to process and more cost-effective, though the optimization of silicon-carbon composites requires precise control over carbon distribution and interface connections, which demands advanced nanocomposite techniques. Silicon primarily addresses the limited capacity of graphite and mitigates volume expansion through structural innovations, while carbon materials improve conductivity and cycling stability by providing a flexible framework that reduces electrode failure caused by expansion. Future trends will concentrate on optimizing the design and scalability of silicon-carbon materials to reduce production costs and improve manufacturability. As more cost-effective composite techniques and surface treatments are developed, silicon-carbon anodes are expected to become a mainstream solution for high-capacity batteries. Future research may explore new coating materials, more efficient conductive networks, or even the integration of solid-state electrolytes to further address issues of volume expansion and enhance energy density and safety. In summary, while silicon-carbon anodes demonstrate tremendous potential for performance improvement, challenges persist regarding engineering complexity, cost control, and long-term stability.

References

[1] Kulova T L, Skundin A M, Pleskov Y V, et al. Lithium insertion into amorphous silicon thin-film electrodes. Journal of Electroanalytical Chemistry, 2007, 600(1): 217-225.

[2] Xie J, Imanishi N, Zhang T, et al. Li-ion diffusion in amorphous Si films prepared by RF magnetron sputtering: A comparison of using liquid and polymer electrolytes. Materials Chemistry and Physics, 2010, 120(2-3): 421-425.

[3] Li J, Xiao X, Yang F, et al. Potentiostatic intermittent titration technique for electrodes governed by diffusion and interfacial reaction. The Journal of Physical Chemistry C, 2012, 116(1): 1472-1478.

[4] Kim H, Han B, Choo J, et al. Three-dimensional porous silicon particles for use in high-performance lithium secondary batteries. Angewandte Chemie International Edition, 2008, 47(52): 10151-10154.

[5] Wang W, Kumta P N. Nanostructured hybrid silicon/carbon nanotube heterostructures: reversible high-capacity lithium-ion anodes. ACS nano, 2010, 4(4): 2233-2241.

[6] Martin C, Crosnier O, Retoux R, et al. Chemical coupling of carbon nanotubes and silicon nanoparticles for improved negative electrode performance in lithium-ion batteries. Advanced Functional Materials, 2011, 21(18): 3524-3530.

[7] Song T, Xia J, Lee J H, et al. Arrays of sealed silicon nanotubes as anodes for lithium ion batteries. Nano letters, 2010, 10(5): 1710-1716.

[8] Zhou X, Yin Y X, Wan L J, et al. Self-assembled nanocomposite of silicon nanoparticles encapsulated in graphene through electrostatic attraction for lithium-ion batteries. Advanced Energy Materials, 2012, 2: 1086-1090.

[9] Ge M, Rong J, Fang X, et al. Scalable preparation of porous silicon nanoparticles and their application for lithium-ion battery anodes. Nano Research, 2013, 6: 174-181.

[10] USCAR, Energy Storage System Goals, 2012; http://uscar.org/guest/article_view.php?articles_id = 85 (acessed August 2013).

[11] Maranchi J P, Hepp A F, Kumta P N. High capacity, reversible silicon thin-film anodes for lithium-ion batteries. Electrochemical and solid-state letters, 2003, 6(9): A198.

[12] Lian P, Zhu X, Liang S, et al. Large reversible capacity of high quality graphene sheets as an anode material for lithium-ion batteries. Electrochimica Acta, 2010, 55(12): 3909-3914.

[13] Liu J, Li Y, Fan H, et al. Iron oxide-based nanotube arrays derived from sacrificial template-accelerated hydrolysis: large-area design and reversible lithium storage. Chemistry of Materials, 2010, 22(1): 212-217.

[14] Wei X, Kang X, Yuan Q, et al. Capture of cesium ions with nanoclusters: effects on inter-and intramolecular assembly. Chemistry of Materials, 2019, 31(13): 4945-4952.

[15] Liu Q, Su X, Lei D, et al. Approaching the capacity limit of lithium cobalt oxide in lithium ion batteries via lanthanum and aluminium doping. Nature Energy, 2018, 3(11): 936-943.

[16] Peng L, Zhao Y, Ding Y, et al. Self-assembled LiFePO4 nanowires with high rate capability for Li-ion batteries. Chemical communications, 2014, 50(67): 9569-9572.

[17] Poorshakoor E, Darab M. Advancements in the development of nanomaterials for lithium-ion batteries: A scientometric review. Journal of Energy Storage, 2024, 75: 109638.

[18] Zhao E, Guo Y, Xin Y, et al. Enhanced electrochemical properties and interfacial stability of poly (ethylene oxide) solid electrolyte incorporating nanostructured Li1.3Al0.3Ti1.7 (PO4)3 fillers for all solid state lithium ion batteries. International Journal of Energy Research, 2021, 45(5): 6876-6887.

[19] Shin W K, Cho J, Kannan A G, et al. Cross-linked composite gel polymer electrolyte using mesoporous methacrylate-functionalized SiO2 nanoparticles for lithium-ion polymer batteries. Scientific reports, 2016, 6(1): 26332.

[20] Epur R. Fundamental study of engineered nanocrystalline and amorphous silicon based high capacity, reversible and stable anodes for lithium-ion batteries. University of Pittsburgh, 2014.

[21] Ge M, Cao C, Biesold G M, et al. Recent advances in silicon-based electrodes: from fundamental research toward practical applications. Advanced Materials, 2021, 33(16): 2004577.

[22] Aliofkhazraei M, Ali N, Milne WI, et al. (Eds.). Graphene Science Handbook: Electrical and Optical Properties (1st ed.). CRC Press. 2016, https://doi.org/10.1201/b19642.