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Silicon anodes in lithium-ion batteries: nanoscale engineering, composite strategies, and industrial prospects

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Silicon (Si) has emerged as one of the most promising anode materials for next-generation lithium-ion batteries (LIBs) due to its extremely high theoretical capacity (3579 mAh g^{-1}), abundant reserves, and inherent safety advantages over conventional graphite anodes. However, the practical application of Si anodes remains hampered by key challenges, including severe volume expansion ($\sim 300\%$), an unstable solid electrolyte interface (SEI), low intrinsic conductivity, and irreversible capacity loss. Academia and industry have invested significant effort in addressing these issues through nanoscale structural engineering, Si-carbon composites, advanced polymer and inorganic binders, artificial SEI coatings, and electrolyte/interface design. Simultaneously, industry has begun to adopt scalable strategies, such as graphite-Si composite hybrids, surface encapsulation, prelithiation, and the integration of fluorinated additives and locally high electrolyte concentrations, to extend cycle life and improve manufacturability. This review focuses on the fundamental mechanisms of Si anodes, summarizes the latest research strategies from both laboratory and industrial perspectives, and explores commercialization pathways through case studies of emerging technologies and global investment. Finally, we outline future research directions and prospects for silicon anodes in advanced battery systems, emphasizing the need to balance performance, cost, and scalability. Silicon is not only a key transition material for high-energy lithium-ion batteries, but also an enabling platform for anode technologies in the post-lithium era.

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1. Introduction

The continued growth of global energy demand, with the urgent need for sustainable and environmentally friendly energy storage solutions, has accelerated the development of high-performance rechargeable secondary batteries.^{1,2} Since their commercialization in the early 1990s, lithium-ion batteries (LIBs) have become the primary power source for portable electronic devices, electric vehicles (EVs), and large-scale energy storage systems due to their high energy density and long cycle life.^{3,4} However, the growing demand for higher energy density and longer driving range in EVs has pushed the traditional graphite anode (372 mAh g^{-1}) close to its theoretical capacity limit,⁵ prompting the search for alternative high-capacity anode materials. Among the many candidate materials, silicon (Si) has received extensive attention from

both academia and industry as a next-generation anode material. Silicon has a high theoretical capacity of 3579 mAh g^{-1} ($\text{Li}_{15}\text{Si}_4$),^{6–8} nearly ten times that of graphite. It also boasts abundant reserves, low cost, and environmental friendliness. Furthermore, silicon's relatively low lithiation potential offers inherent safety advantages, avoiding lithium deposition, a common problem with fast-charging graphite anodes.⁹ These unique properties make silicon one of the most promising materials for high-energy lithium-ion batteries.

Despite these advantages, the practical deployment of Si anodes faces significant challenges. The most critical issue is the drastic volume change ($\sim 300\%$)¹⁰ during lithiation/delithiation, which induces particle pulverization, loss of electrical contact, and rapid capacity fading. Additionally, the repeated expansion and contraction lead to continuous rupture and reformation of the solid electrolyte interphase (SEI), resulting in unstable interfaces, increased impedance, and low coulombic efficiency.^{11,12} Moreover, the intrinsically low electrical conductivity¹³ and sluggish lithium-ion diffusivity of Si further aggravate the performance degradation, especially under high current densities. Over the past two decades, extensive research has been devoted to overcoming these challenges. Academic studies have explored various strategies, including nanoscale structural design (nanowires,

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hollow structures, and porous Si), Si-carbon composites,¹⁴ advanced polymeric and inorganic binders,¹⁵ artificial SEI layers,¹⁶ and optimized electrolytes with functional additives.¹⁷ These approaches have demonstrated significant improvements in mitigating volume changes, enhancing mechanical stability, and improving interfacial robustness.¹⁸

In parallel, industrial research has focused on translating these concepts into scalable and cost-effective solutions.¹⁹ Current commercial practices include blending Si with graphite to form composite anodes, applying surface encapsulation or coating layers, introducing pre-lithiation techniques to compensate for initial capacity loss, and employing fluorinated additives or localized high-concentration electrolytes to stabilize the SEI.²⁰ Companies worldwide, including leading battery manufacturers and startups, are investing heavily in Si-based anode technologies, and partial commercialization has already been achieved in electric vehicles and consumer electronics.

In this review, we aim to provide a comprehensive overview of Si anode research and development from both academic and industrial perspectives. We first introduce the fundamental lithiation mechanisms and the associated degradation phenomena of Si anodes. We then summarize recent progress in structural engineering, material design, interface regulation, and electrolyte optimization. Furthermore, we highlight industrial strategies, manufacturing considerations, and commercialization pathways through representative case studies. Finally, we discuss the prospects and challenges for future research, emphasizing the balance between electrochemical performance, scalability, and economic viability. We believe that Si, as a transitional and enabling material, will play a pivotal role not only in advancing high-energy lithium-ion batteries but also in shaping the development of post-lithium energy storage technologies.

2. Fundamentals of silicon anodes

2.1 Theoretical background

Silicon (Si) has attracted significant attention as a next-generation anode material for lithium-ion batteries (LIBs) owing to its exceptionally high theoretical capacity ($\sim 3579 \text{ mAh g}^{-1}$ for $\text{Li}_{15}\text{Si}_4$), which is nearly an order of magnitude greater than that of conventional graphite (372 mAh g^{-1} for LiC_6). This high capacity originates from the electrochemical alloying reaction between Li and Si, which involves complex, multi-step phase transformations and solid-state diffusion processes during lithiation and delithiation.²¹ At room temperature, the lithiation of crystalline silicon (c-Si) is often described as an initial two-phase reaction, where Li insertion leads to the formation of amorphous Li_xSi ($0 < x < \sim 3.5$),²² accompanied by substantial volume expansion (up to $\sim 300\%$). Under certain conditions—such as sufficiently low cutoff voltages, large particle sizes, and specific cycling protocols—further lithiation may result in the formation of crystalline $\text{Li}_{15}\text{Si}_4$ at potentials near 60 mV vs. Li/Li^+ .²³ However, it should be noted that the formation of $\text{Li}_{15}\text{Si}_4$ is not universal and can be suppressed in nanoscale silicon, amorphous structures, or under limited lithiation depths, highlighting the strong dependence of the reaction pathway on particle size, crystallinity, and electrochemical conditions.

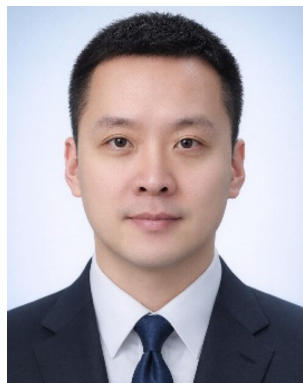
During delithiation, the reaction pathway is typically asymmetric. When $\text{Li}_{15}\text{Si}_4$ is formed, it generally transforms back into amorphous Li_xSi and eventually into a metastable amorphous Si phase, rather than reverting to the original crystalline Si, indicating an irreversible structural evolution after the initial cycle.²⁴ Such repeated amorphous-crystalline and crystalline-amorphous transitions, when present, can induce significant internal stress, fracture, and pulverization of Si par-



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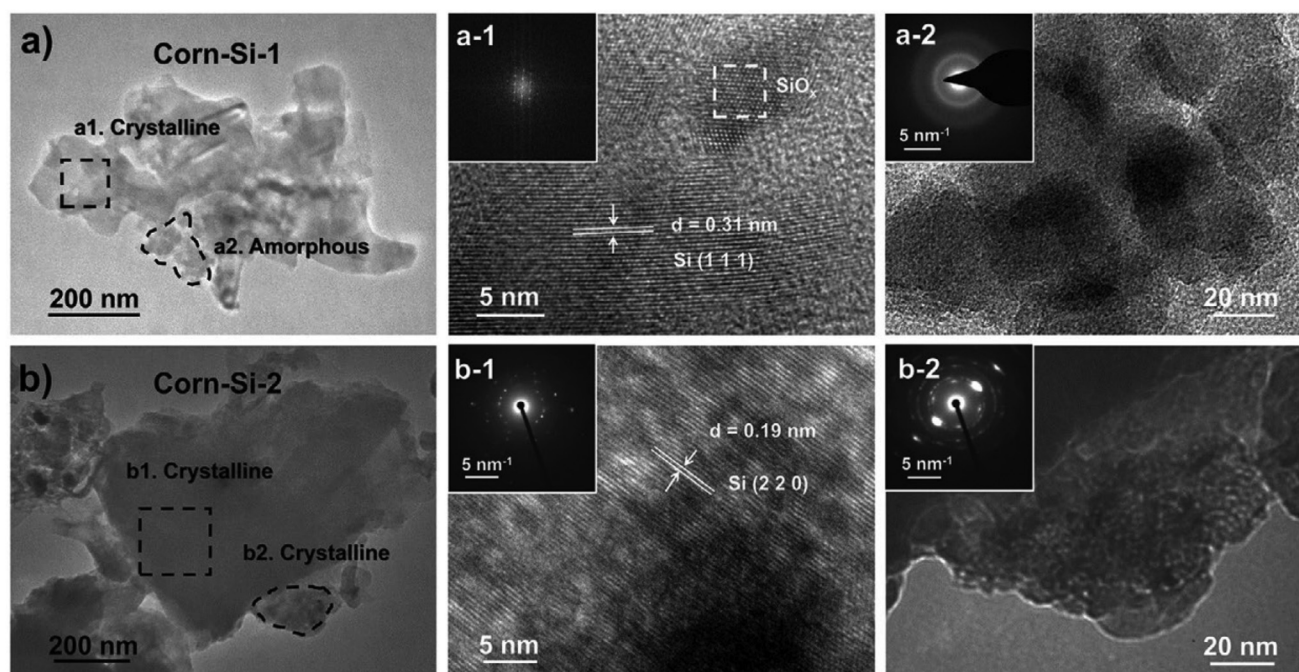


Fig. 1 (a) TEM image of the Corn-Si-1 sample. (a-1) HRTEM image of the crystalline part of Corn-Si-1. (Inset: FFT image.) (a-2) HRTEM image of the amorphous part of Corn-Si-1. (Inset: SAED image.) (b) TEM image of the Corn-Si-2 sample. (b-1 and b-2) HRTEM image of the crystalline part of Corn-Si-2. (Inset: SEAD image.) Adapted with permission from ref. 25. Copyright 2020@Wiley.

ticles, leading to electrical disconnection and rapid capacity decay. The distinction between crystalline and amorphous states is more clearly illustrated in Fig. 1. Moreover, the large volume fluctuations continuously disrupt the solid electrolyte interphase (SEI), resulting in repeated formation and rupture, which further consumes active lithium and the electrolyte. Therefore, a comprehensive understanding of the thermodynamics and kinetics of Li-Si alloying—including Li diffusion, phase boundary evolution, and nucleation ener-

getics—is essential for the rational design of stable Si-based anodes. To mitigate these challenges, various strategies have been developed, such as nanoscale structuring, utilization of amorphous silicon, alloying with inactive or active matrices, and artificial SEI engineering.

2.2 Key issues

2.2.1 Large volume expansion (~300%). One of the most critical challenges associated with silicon anodes is their pronounced volumetric change during lithiation/delithiation. Silicon undergoes a theoretical volume expansion of nearly 300% upon full lithiation to $\text{Li}_{15}\text{Si}_4$, leading to severe mechanical stress, particle fracture, interfacial delamination, and electrode pulverization. These structural degradations disrupt electronic pathways and accelerate SEI instability, ultimately causing rapid capacity fading.

To address these issues, various structural design strategies have been developed, which can be broadly categorized into one-dimensional (1D) nanostructures, porous architectures, and composite frameworks. One-dimensional nanostructures provide efficient strain relaxation pathways along the radial direction, effectively mitigating mechanical degradation. Son *et al.*²⁶ synthesized four types of 1D silicon nanostructures (SiNW, SiNT, L-SiNW, and GeSiNW) via electrospinning followed by magnesiothermic reduction. By controlling precursor composition, different spatial distributions of internal buffer spaces were achieved. The concept of space for alleviating volume expansion (SAV) was introduced to describe stress/strain relaxation during lithiation. Structures with well-



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designed SAV (e.g., SiNT, L-SiNW, and GeSiNW) exhibited reduced volume expansion and improved electrochemical performance compared to dense SiNW, highlighting the importance of buffer space distribution (Fig. 2A). Porous structures accommodate volume expansion through internal voids while maintaining structural integrity. Dai *et al.*²⁷ developed hierarchical porous silicon (hp-Si) with tunable primary (20–200 nm) and secondary (~3–10 nm) pores. The interconnected pore network effectively buffers volume changes, while

larger primary pores enhance electrode durability and maintain fast ion transport pathways, leading to improved capacity retention and rate capability (Fig. 2B). Integrating silicon with conductive matrices provides mechanical confinement and improves charge transport. Xiao *et al.*²⁸ demonstrated that embedding amorphous Si nanoparticles into porous carbon frameworks can effectively mitigate volume expansion. However, the pore volume of the carbon matrix plays a critical role; an optimal balance between pore volume and Si loading

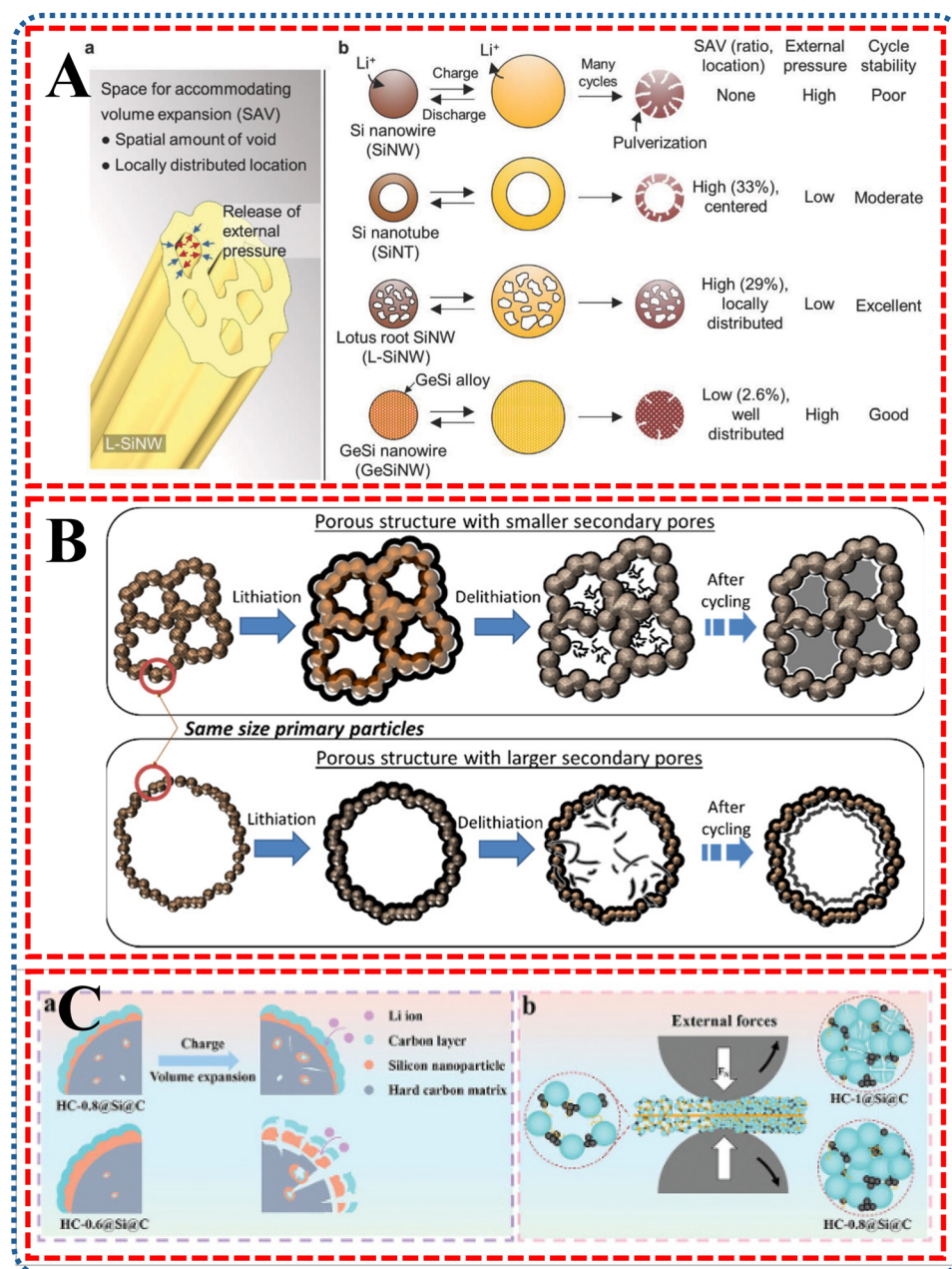


Fig. 2 (A) (a) Illustration of L-SiNW describing the space for accommodating volume expansion during Li insertion and extraction. (b) Schematic of the charging and discharging processes of SiNW, SiNT, L-SiNW, and GeSiNW and the summary of their spatial ratio and location of SAV, external pressure, and cycle performance. (B) Schematic of minimized volume expansion in hierarchical porous silicon upon lithiation. (C) Schematic illustration of (a) the lithiation process of HC-0.8@Si@C and HC-0.6@Si@C, and (b) the external forces acting on HC-1@Si@C and HC-0.8@Si@C. Adapted with permission from ref. 26–28. Copyright 2018@Wiley; Copyright 2019@ACS; Copyright 2024@Wiley.

is required to ensure structural stability, efficient ion/electron transport, and long-term cycling performance (Fig. 2C).

2.2.2 Mechanical pulverization and SEI instability. The excessive volume fluctuation induces mechanical pulverization of Si particles, causing them to fracture into smaller fragments. This phenomenon increases the effective surface area exposed to the electrolyte, leading to uncontrolled formation and repeated rupture of the solid electrolyte interphase (SEI). Since SEI formation is a passivation process that consumes both lithium ions and electrolyte components, its repeated breakdown and reformation result in continuous loss of active lithium, increased interfacial resistance, and severe capacity fading.²⁹ Furthermore, the inhomogeneous stress distribution promotes uneven SEI growth, forming thick and unstable layers that impede ion transport. The instability of the SEI

layer also leads to parasitic reactions and gas evolution, compromising the long-term electrochemical stability of the battery. Pretreatment of silicon anodes is an important method to improve the SEI stability. Li *et al.*³⁰ developed a polymer polyhedral oligomeric silsesquioxane-lithium bis(allylmalonato)borate (PSLB) on microscale Si anodes that accommodates volume changes and stabilizes the SEI through an organic/inorganic hybrid cross-linked structure. Within the stable framework provided by PSLB, abundant oxide anions along the polymer chains preferentially interact with LiPF₆, promoting the formation of a dense, inorganic-rich SEI, thereby enhancing its mechanical stability and facilitating faster Li⁺ transport. This strategy enhances mechanical stability and Li⁺ transport, enabling the Si₄@PSLB anode to deliver high capacity (1083 mAh g⁻¹) over 300 cycles and maintain

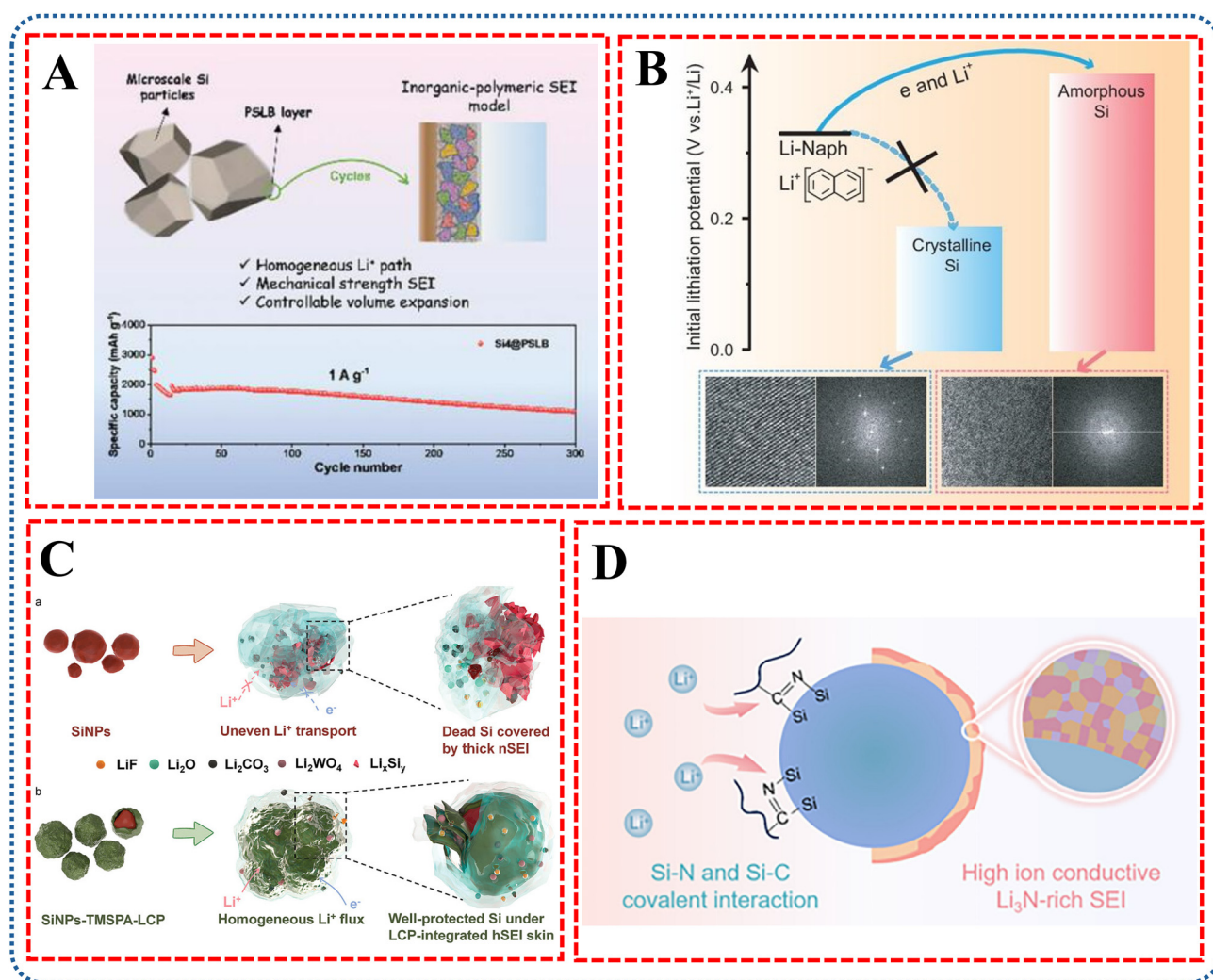


Fig. 3 (A) Schematic diagram of a uniform self-reinforced organic/inorganic hybrid SEI chelation strategy on microscale silicon surfaces for stable-cycling anodes in lithium-ion batteries. (B) Schematic diagram of the effect of silicon structure on the initial lithiation potential and prelithiation behavior. (C) Schematic of the evolution of interfacial stability and the SEI microstructure. (a) Pristine SiNPs with thick nSEI. (b) LCP-coated SiNPs with LCP-integrated hSEI skin. (D) Schematic of formation of a robust SEI through covalent binding of nitrile to silicon toward stabilized micron-sized silicon anodes. Adapted with permission from ref. 30–33. Copyright 2023@Wiley; Copyright 2025@Oxford; Copyright 2022@Wiley; Copyright 2025@Elsevier.

80.8% capacity retention in NCM90 full cells (Fig. 3A). Quan *et al.*³¹ showed that amorphous silicon anodes can be effectively prelithiated with lithium naphthalenide (Li-Naph), and lithium ions and electrons from the Li-Naph reagent can be transferred to amorphous silicon with a higher lithiation potential, whereas such transfer is hindered in crystalline silicon due to its lower lithiation potential (Fig. 3B). Prelithiation (*via* Li-Naph) regulates electrolyte decomposition, promoting the formation of a thicker, LiF-rich SEI with uniform distribution. It also favors BF_4^- -derived species, leading to an SEI enriched in F- and B-containing components, which enhances interfacial stability and Li^+ transport. This approach raised the initial coulombic efficiency from 74.8% to 97.2% and enabled pouch cells to retain 90.1% capacity after 800 cycles at 1C, demonstrating a scalable strategy for high-performance silicon anodes. Besides, polymer coatings and adhesives are effective solutions. Pan *et al.*³² developed a layered conductive polyaniline (LCP) coating on Si nanoparticles, which directs the formation of a hybrid SEI with a uniform distribution of organic and inorganic components. The conformal LCP layer retains the electrolyte within its interlaminar spaces and promotes the *in situ* formation of an LCP-integrated SEI, enhancing interfacial flexibility to accommodate volume changes while maintaining homogeneous ion transport during cycling. As a result, the flexible SEI effectively buffers volumetric fluctuations and enables high areal capacity ($\sim 3 \text{ mAh cm}^{-2}$), along with excellent cycling stability and rate capability (942 mAh g^{-1} at 5 A

g^{-1}) (Fig. 3C). The nitrile groups in the PAN binder form strong Si-N covalent bonds on the Si surface, enhancing mechanical integrity and effectively suppressing crack formation and pulverization during volume expansion. Meanwhile, these Si-N bonds induce the *in situ* formation of a Li_3N -rich inner SEI layer, leading to a robust bilayer SEI composed of a Li_3N -rich inner layer and an organic-rich outer layer. This N-rich SEI not only stabilizes the electrode/electrolyte interface but also enhances ionic conductivity and mechanical flexibility. As demonstrated by Zhao *et al.*,³³ such a structure enables silicon electrodes to achieve high coulombic efficiency, excellent rate capability, and long-term cycling stability (1290 mAh g^{-1} over 800+ cycles at 0.5C) (Fig. 3D).

2.2.3 Poor intrinsic conductivity. Silicon exhibits low intrinsic electronic conductivity ($\sim 10^{-3} \text{ S cm}^{-1}$) and limited lithium-ion diffusivity ($\sim 10^{-14}$ to $10^{-12} \text{ cm}^2 \text{ s}^{-1}$), which hinder the charge transfer kinetics and result in poor rate performance.¹³ During lithiation, the formation of high Li-Si alloy phases further exacerbates the resistive nature of the electrode.³⁴ The sluggish electron and ion transport can cause localized lithiation, leading to uneven volume expansion and non-uniform stress distribution.³⁵ This issue is particularly critical for bulk Si particles, where the diffusion length exceeds the intrinsic diffusion capabilities, making full utilization of the active material difficult under high current densities. By adopting different silicon composite materials, the electronic conductivity of the silicon anodes can be effectively improved. Wu *et al.*³⁶ employed polycarbosilane (PCS) as a pre-

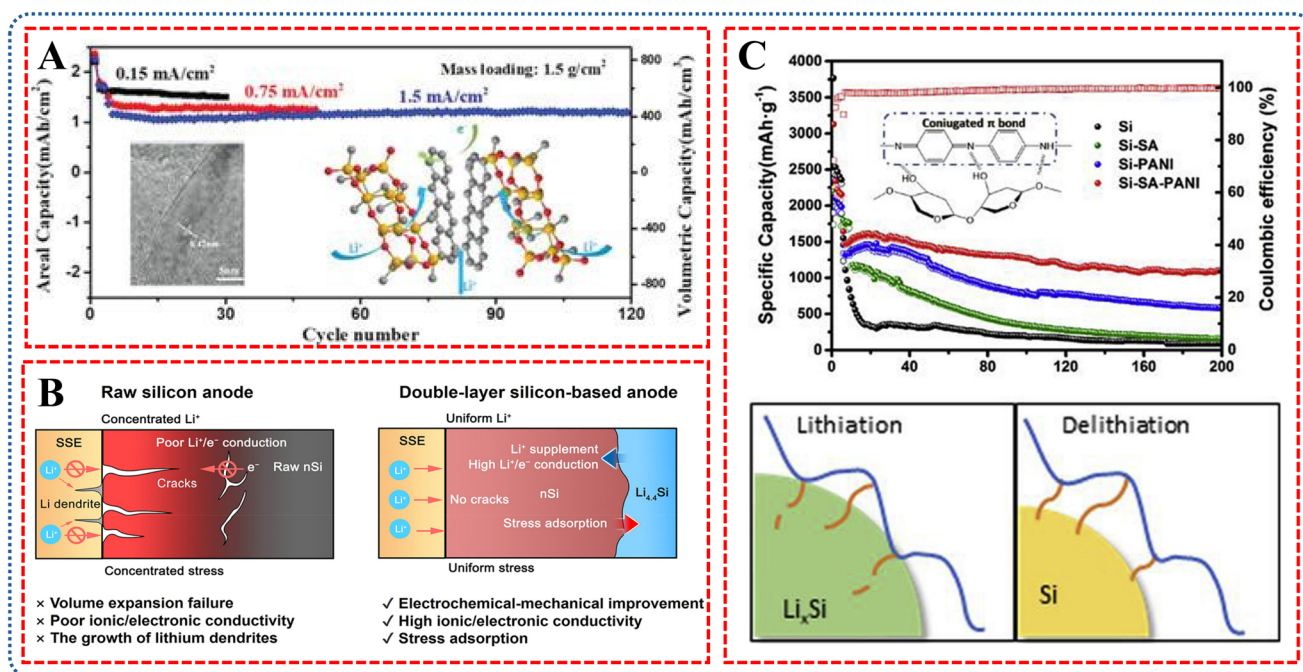


Fig. 4 (A) Schematic of SiOC phase control and carbon nanoribbon growth by introducing oxygen at the atom level for lithium-ion batteries. (B) Schematic of electrochemical-mechanical synergistic regulation by constructing a double-layer fully active silicon-based alloy anode in sulfide all-solid-state batteries. (C) Schematic of self-healing silicon-sodium alginate-polyaniline composites originating from the enhancement of hydrogen bonding for the lithium-ion battery. Adapted with permission from ref. 36–38. Copyright 2022@Wiley; Copyright 2025@Elsevier; Copyright 2019@Elsevier.

cursor to design SiOC ceramics with atom-level control of oxygen and carbon content *via* air oxidation cross-linking. This strategy enhances intrinsic conductivity and reversible lithium storage, achieving excellent rate capability, high areal/volumetric capacity, and improved the initial coulombic efficiency, providing a novel approach to optimize SiOC anodes through precursor structure design (Fig. 4A). Huang *et al.*³⁷ designed a double-layer silicon anode for sulfide all-solid-state batteries, combining a $\text{Li}_{4.4}\text{Si}$ alloy layer with a nano-Si layer. This structure improves Li^+ transport and electron conductivity, and buffers volume-change-induced stress, leading to reduced interfacial stress, 86.5% capacity retention over 200 cycles at 0.5C, and a high cell-level energy density of $308.04 \text{ Wh kg}^{-1}$, demonstrating strong potential for scalable ASSB applications (Fig. 4B). Mi *et al.*³⁸ developed silicon-sodium alginate-polyaniline composites with a 3D conductive network, where hydrogen-bond self-healing accommodates volumetric changes during cycling. This design enhances electron transport, mechanical integrity, and conductivity, enabling the anode to deliver $1099.5 \text{ mAh g}^{-1}$ over 200 cycles at 1 A g^{-1} and providing a scalable strategy to mitigate silicon pulverization (Fig. 4C).

2.2.4 Irreversible capacity loss (ICL). Silicon-based anodes typically exhibit a large initial irreversible capacity loss (ICL) during the first cycle, primarily originating from the formation of the solid electrolyte interphase (SEI) and lithium trapping within the amorphous Si or Li_xSi matrix. These processes irreversibly consume active lithium, leading to a significant reduction in the initial coulombic efficiency (ICE) and limiting the practical energy density of full cells.

From a mechanistic perspective, lithium trapping plays a dominant role in ICL. Li *et al.*³⁹ revealed that Li trapping, together with volume expansion and unstable SEI, critically affects the cycling stability of silicon anodes. They identified two types of trapped lithium: active Li associated with sluggish kinetics and inactive Li induced by structural degradation, such as Si pulverization. Notably, inactive Li dominates capacity loss after cycling, highlighting the importance of suppressing structural instability and irreversible phase evolution (Fig. 5A). In addition, the irreversible transformation from crystalline Si to amorphous Si during the first lithiation further aggravates lithium immobilization and long-term capacity decay. To mitigate ICL and improve ICE, various strat-

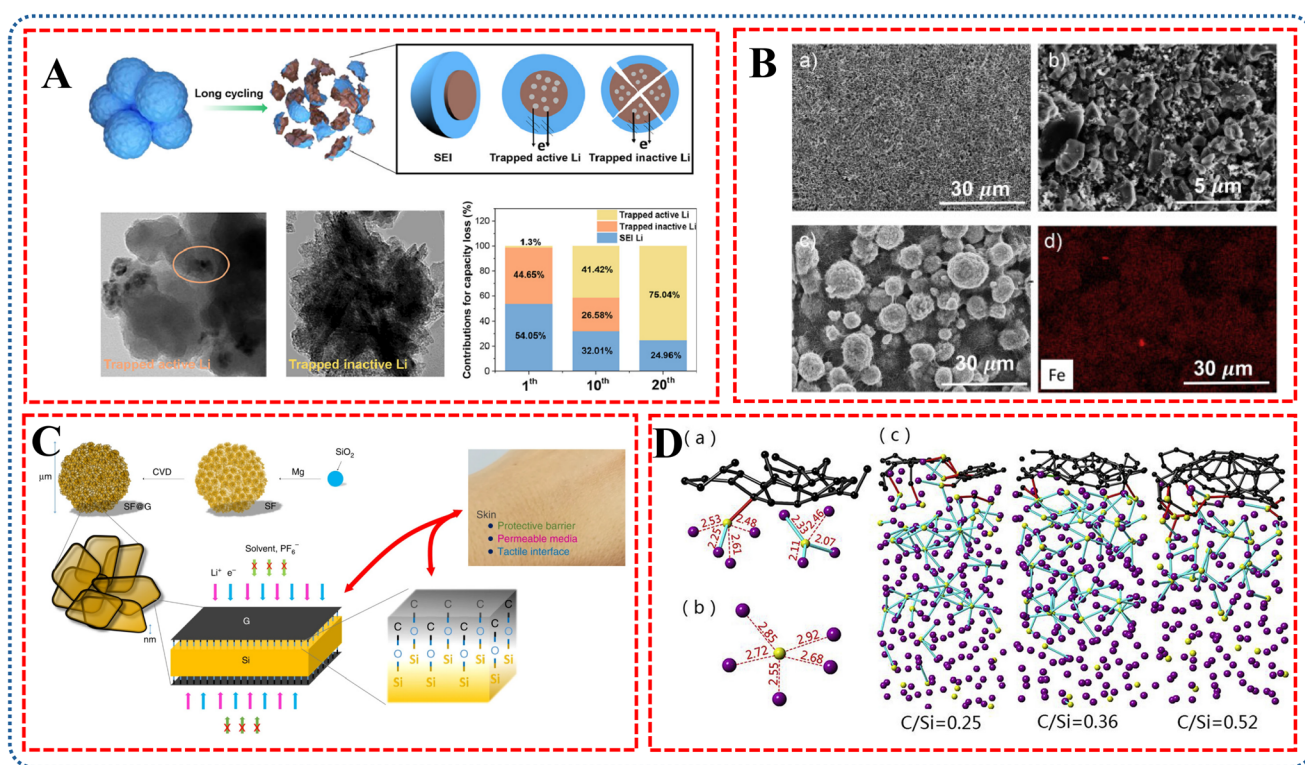


Fig. 5 (A) Schematic of an electrochemical-mechanical unveiling of the mechanism of Li-trapping induced (ir)reversible capacity loss for the silicon anode. (B) (a, b) SEM images of uncycled SiO anodes and (c) the uncycled NCM-LFO blend cathode; (d) EDS mapping of the Fe signal for the uncycled NCM-LFO blend cathode. (C) Schematic of the fabrication process for SF@G. The synthesized SF@G features a two-dimensional covalently bound component interface, enabling stable and fast electron (e^-) and lithium-ion (Li^+) transport, while fundamentally blocking undesirable substances such as the electrolyte solvents (EC, DEC) and anions (PF_6^-), mimicking the skin functions typically as a protective barrier, a permeable medium, and a tactile interface. (D) Some typical zoomed-in atomic configurations in the fully lithiated silicon-carbon interfacial structures. (a) Formation of the Si-C bond and lengths of Si-Li bonds (in Å) at the silicon-carbon interface, (b) bond lengths for the Si-Li bond in the silicon portion, and (c) the lithiated interfacial structures for different models. The black, yellow and violet spheres represent the C, Si and Li atoms, respectively. Adapted with permission from ref. 39–42. Copyright 2023@Elsevier; Copyright 2018@Elsevier; Copyright 2020@ Springer; Copyright 2019@Elsevier.

gies have been developed. Prelithiation strategies are widely employed to compensate for lithium loss in the initial cycle. For example, Zhang *et al.*⁴⁰ demonstrated that introducing Li_5FeO_4 as a prelithiation reagent into the NCM523 cathode effectively alleviates the initial capacity loss of SiO anodes, improving lithium utilization and significantly enhancing full-cell capacity retention (Fig. 5B).

Interfacial and structural engineering also plays critical roles in suppressing irreversible reactions and stabilizing the electrode. Zhang *et al.*⁴¹ proposed a two-dimensional covalent encapsulation strategy to construct Si-C hybrid structures, which stabilize the electrode/electrolyte interface and facilitate rapid ion/electron transport, thereby improving ICE, reversibility, and rate capability (Fig. 5C). Similarly, Zhang *et al.*⁴² showed that optimizing carbon coating thickness in silicon-carbon film anodes can effectively balance the initial capacity and long-term stability. While thicker carbon layers reduce the first-cycle discharge capacity, they enhance cycling stability and rate performance by improving electronic conductivity and Li^+ diffusion (Fig. 5D). Overall, improving ICE in silicon anodes requires a synergistic approach that combines lithium compensation with interfacial and structural regulation, aiming to minimize irreversible lithium consumption and enhance electrochemical reversibility.

3. Current status of silicon anodes in industry

3.1 Design logic governing industrial application and technology stages

The industrial adoption of silicon anodes in lithium-ion batteries is not determined solely by the superiority of theoretical capacity, but follows a constrained evolutionary process governed by trade-offs among energy density, mechanical stability, and manufacturing process compatibility. In particular, silicon provides high capacity while simultaneously exhibiting severe volume expansion during charge-discharge processes, low initial coulombic efficiency (ICE), and interfacial instability, which can lead to repeated SEI formation and structural degradation of the electrode. These limitations become more pronounced in large-format EV cells.

Importantly, the translation from half-cell performance to practical full-cell systems remains a critical challenge. Many literature reports emphasize high specific capacity and long cycle life obtained under half-cell conditions with low areal loading, excess lithium, and high electrolyte content, which are not representative of realistic battery configurations. In practical cells, key engineering parameters—including areal loading, electrode density, N/P ratio, electrolyte amount (E/C), prelithiation requirements, electrode swelling, and volumetric energy density—play a decisive role in determining overall performance. For silicon-based anodes, these parameters are strongly coupled to intrinsic material limitations. For example, the large volume expansion restricts electrode densification, resulting in low tap density and poor volumetric energy

density, while low ICE necessitates prelithiation strategies that introduce additional complexity and cost. Moreover, the high specific surface area of silicon-rich structures increases electrolyte consumption and exacerbates SEI formation, making it difficult to achieve practical E/C ratios. Therefore, optimizing silicon anodes for real-world applications requires a system-level balance rather than maximizing intrinsic material capacity alone.

Due to these constraints, industry has adopted a strategy of incorporating silicon in a limited manner into graphite-based structures rather than using silicon alone. In mass-produced EV cells, Si-C composite structures containing approximately 3–8 wt% silicon have become the dominant approach, and the IEA has reported that silicon-doped graphite has already entered the market and is being applied in a significant fraction of anodes.⁴³ Such industrial application can be classified into stages according to silicon content. In general, the low-silicon regime below 10 wt% represents the mainstream commercialization stage in the current EV market, prioritizing stability and cycle life. A silicon content of approximately 10–20 wt% is considered a transitional stage for improving energy density, where achieving a balance between performance enhancement and structural stability becomes the main challenge. In contrast, high-silicon systems above 20 wt%, despite offering high capacity, are limited in their stable application in large-format EV cells due to severe volume expansion and low initial coulombic efficiency, and remain primarily at the level of evaluation in small electronic devices or certain specialized applications.

From a materials perspective, this stage classification is not merely compositional, but reflects fundamental differences in electrochemical and mechanical behavior. SiO_x -based materials can alleviate volume expansion and achieve relatively high initial coulombic efficiency through an oxygen-containing matrix, but exhibit limited capacity due to the presence of partially inactive oxides.^{44,45} In contrast, Si-C composites provide improved electronic conductivity and mechanical stability through a conductive carbon network, making them more suitable for low-silicon regimes. High-silicon structures offer higher capacity but suffer from pronounced structural instability and are therefore currently restricted to limited or emerging applications.

Therefore, the industrial development of silicon anodes can be understood as a stepwise evolution in which silicon content is gradually increased based on a balance among multiple performance constraints, rather than the maximization of a single material property.

3.2 Commercialization cases by material pathway and industrial development

It is more appropriate to organize commercialization cases based on material pathways and application markets rather than by country. The current industrial development of silicon anodes can be classified into graphite-compatible low-silicon/ SiO_x pathways, high-silicon Si-C composite scale-up pathways, and nanostructured high-energy niche pathways.

First, the graphite-compatible low-silicon/ SiO_x pathway is regarded as the most practical commercialization route for large-format EV cells. This pathway originated in the early 2010s with the introduction of silicon-doped graphite in small cells, and has evolved toward large-scale EV platforms with a focus on stability and cycle life.⁴³

Daejoo Electronic Materials presents DMSO as a silicon-based anode material and introduces it as a mass-producible SiO_x material applicable to EVs, power tools, smartphones, and drone batteries, and operates a dedicated business for silicon-based anode materials. This SiO_x pathway can be understood as a strategy that alleviates volume expansion through an oxygen-containing matrix while maintaining compatibility with conventional graphite electrode processes and achieving gradual performance improvements. BTR also presents both silicon monoxide composites and silicon-carbon composites as product lines, indicating that in industry, SiO_x and Si-C are not in a competitive relationship but are applied in parallel depending on application requirements.

This approach is also consistent with the current trend in EV cells, where low-silicon Si-C composite structures dominate. In Tesla's 4680 cells, Gen1 employed a 100% graphite anode,⁴⁶ followed by the introduction of silicon in later generations,⁴⁷ and at Battery Day (2020), a strategy for gradually increasing silicon content using low-cost silicon and polymer-based processing was proposed.⁴⁸

Next, the high-silicon Si-C composite scale-up pathway has been actively developed since the 2020s. This pathway aims for higher energy density compared to low-silicon blends, while still relying on carbon compositing and process stability.

Sila has introduced Titan Silicon as a next-generation automotive anode material and has been preparing for mass production centered on the Moses Lake plant during 2024–2025 following its brand announcement in 2023. Group14 has also been expanding EV-scale production based on SCC55 through large-scale investment and the establishment of production sites in 2025. These developments indicate that high-silicon adoption is moving beyond material development into a stage involving manufacturing scale-up and supply chain establishment. However, this pathway still maintains a Si-C composite structure rather than pure silicon, which can be interpreted as a structural compromise to mitigate volume expansion and initial efficiency issues at high silicon content.

In contrast, the nanostructured high-energy niche pathway is primarily developing in applications such as aviation, UAVs, and specialized mobility, where energy density is prioritized over large-scale EV deployment. Amprius has announced SiCore cells with 450–500 Wh kg^{-1} in 2025 and is expanding supply to aviation and UAV markets. This nanowire-based approach is advantageous for achieving high capacity and direct electron pathways, but due to cost and process complexity, it is currently applied mainly in limited high-value applications rather than in mainstream EV markets.

In China, a parallel expansion strategy of Si-C and SiO_x pathways is observed. The trial production of silicon-carbon projects by Putailai and the continued mass production claims

of nano Si-C materials by IOPSILION indicate ongoing supply chain expansion. However, as these cases are largely based on company disclosures and industry reports, it is more appropriate to interpret them as being at the stage of production expansion rather than full-scale commercialization in large EV cells.

Thus, commercialization cases of silicon anodes exhibit a structure in which different material pathways are developed in parallel depending on application requirements and performance constraints.

3.3 Industrial implications and future directions

Globally, the adoption of silicon-based anodes is expanding gradually around low-silicon Si-C structures, consistent with IEA reports and industrial outlooks. This trend can be understood not as the diffusion of a single technology, but as the result of multiple pathways developing in parallel according to the electrochemical and mechanical constraints of each material system.

In particular, high-silicon systems offer high capacity but are limited in large-format EV applications due to severe volume expansion and low initial coulombic efficiency, whereas Si-C and SiO_x -based structures provide a more balanced combination of structural stability and process compatibility, making them practical choices in the current EV market. As a result, a dual application pattern emerges, in which low-silicon strategies dominate in EV applications, while high-silicon approaches are applied in a limited manner in aviation and premium applications.

This structure suggests that future commercialization of silicon anodes will be determined not by a simple increase in silicon content, but by achieving stability in the intermediate silicon regime and by the integrated optimization of materials, processing, electrolytes, and cell design. In this sense, the industrial development of silicon anodes is expected to proceed as a staged expansion from low-silicon systems, with progress dependent on resolving structural constraints at each stage.

4. Strategies to overcome challenges

4.1 Nanostructuring of silicon

Since the emergence of nanoscale silicon, nanotechnology has played a pivotal role in advancing particle design through nano/microstructuring strategies.⁴⁹ However, silicon nanoparticles still suffer from limited electrical conductivity and insufficient stress accommodation during cycling. To address these issues, multidimensional nanostructures ranging from one-dimensional to three-dimensional architectures have been developed,^{50,51} offering improved structural connectivity and electron transport compared to their zero-dimensional counterparts. Representative designs, including nanowires,⁵² nanotubes,^{53,54} and hollow or yolk-shell structures,^{55,56} can effectively accommodate the ~300% volume expansion of silicon by providing internal void space and shortened ion diffusion pathways. For example, Si nanowires grown on current collectors enable direct electron transport, while

hollow structures allow inward expansion without structural fracture, thereby enhancing cycling stability and rate capability.

Despite these advantages, nanostructured silicon remains challenged by low tap density, high fabrication cost (*e.g.*, CVD or template-assisted synthesis), and excessive interfacial side reactions due to high surface area, which lead to severe SEI formation and low initial coulombic efficiency. Several studies have demonstrated strategies to overcome these limitations: recent advances in silicon nano-engineering have focused on integrating structural design with interfacial and compositional modulation to simultaneously address volume expansion, conductivity, and cycling stability. For instance, hollow carbon frameworks combined with one-dimensional silicon structures have been widely adopted to enhance structural resilience. Li *et al.*⁵⁷ developed Si nanowires embedded in nitrogen-doped hollow carbon spheres, delivering a reversible capacity of $\sim 568 \text{ mAh g}^{-1}$ after 200 cycles and maintaining high-rate capability (up to 1028 mAh g^{-1} at 8 A g^{-1}), where the hollow architecture buffers volume expansion while the conductive carbon matrix and embedded metallic nanoparticles facilitate electron transport (Fig. 6A). Similarly, Yin *et al.*⁵⁸ reported Si nanoparticles confined within hollow N-doped carbon microspheres, achieving $\sim 872 \text{ mAh g}^{-1}$ after 360 cycles, demonstrating that uniform encapsulation effectively suppresses volumetric fluctuation and enhances long-term stability (Fig. 6B).

Beyond conventional templating approaches, alternative strategies incorporating sustainability and structural integration have also emerged. Shen *et al.*⁵⁹ converted waste silicon into amorphous Si nanowires *via* a carbon thermal shock process, forming self-supporting electrodes with high initial coulombic efficiency ($\sim 91.35\%$) and stable cycling ($\sim 2150 \text{ mAh g}^{-1}$ at 2 A g^{-1} over 250 cycles), highlighting the potential for scalable silicon utilization. In parallel, multi-component hybrid structures have been explored to further optimize interfacial stability and conductivity (Fig. 6C). Chen *et al.*⁶⁰ constructed Cu_3Si -modified Si nanoparticles encapsulated within SiO_x and hollow carbon shells, achieving $\sim 1150 \text{ mAh g}^{-1}$ at low current density and maintaining $\sim 450 \text{ mAh g}^{-1}$ even at 8.4 A g^{-1} , along with 86.3% capacity retention after 200 cycles, where the synergistic effects of metal silicide, oxide matrix, and conductive carbon enhance both structural stability and charge transport (Fig. 6D).

Collectively, these studies demonstrate that effective silicon anode design increasingly relies on the coupling of hollow/porous architectures, conductive carbon frameworks, and interfacial engineering (*e.g.*, doping, alloying, or oxide incorporation) to mitigate mechanical degradation and stabilize electrochemical performance. However, despite these advantages, such nanostructured and hollow systems often suffer from low tap density and reduced volumetric energy density due to their high porosity and complex architectures. This highlights an inherent trade-off between gravimetric capacity and practical electrode-level performance, suggesting that future efforts should focus on balancing structural stability with electrode densification and scalable manufacturing.

4.2 Silicon-carbon composites

The integration of silicon with various forms of carbon is a widely adopted strategy to enhance electrical conductivity and mitigate mechanical stress. Graphite/Si blends represent a commercially relevant approach, combining the high capacity of Si with the structural stability and conductivity of graphite.⁶¹ In addition, amorphous carbon coatings, graphene sheets, and carbon nanotube (CNT) networks can form conductive matrices that buffer the severe volume change ($\sim 300\%$) of Si during lithiation/delithiation while maintaining continuous electronic pathways. These composites not only alleviate electrode pulverization but also suppress electrical disconnection and partially stabilize the solid electrolyte interphase (SEI) by mitigating the so-called “dynamic interfacing” between Si and the electrolyte.

However, despite these advantages, conventional carbon integration strategies are primarily based on physical contact or weak interfacial interactions, which are insufficient to fully accommodate the repeated volume fluctuation of Si and often lead to unstable interfacial evolution and continuous SEI growth. In this regard, more robust interfacial engineering, such as two-dimensional covalent Si-C encapsulation, has been proposed to establish strong and stable bonding between silicon and conductive carbon frameworks. This skin-like covalent binding not only ensures efficient electron/ion transport but also fundamentally stabilizes the Si/electrolyte interface, thereby enabling improved cycling stability, high capacity, and rate capability.⁶² Nevertheless, challenges still remain in achieving uniform carbon coating and precisely controlling the Si loading ratio, as excessive Si content often leads to structural instability, whereas insufficient Si reduces the overall energy density. For example, Son *et al.*⁶³ developed a nanocage-shaped silicon-carbon composite anode exhibiting excellent pseudocapacitive behavior for lithium-ion batteries. The ultrathin Si layer provides a high pseudocapacitive contribution, yielding superior rate capability compared to conventional Si-based anodes. Additionally, the 3D cage-like pore structure accommodates volume expansion during lithiation, resulting in high cycling stability, offering a promising design for high-power and high-energy LIB anodes (Fig. 7A). Sohn *et al.*⁶⁴ developed a semimicro-sized silicon-carbon (mSi-C) composite anode *via* a scalable aerosol-assisted process, consisting of $\sim 100 \text{ nm}$ Si nanoparticles coated with a conductive carbon layer. The composite exhibits high reversible capacity (2084 mAh g^{-1} at 0.4 A g^{-1}), excellent cycling stability (96% retention after 50 cycles), good rate capability (906 mAh g^{-1} at 12 A g^{-1}), and high tap density (0.448 g cm^{-3}) corresponding to 933 mAh cm^{-3} volumetric capacity. Its performance is attributed to the unique composite structure accommodating Si volume changes, facilitating ion transport, and the conformal carbon coating enhancing conductivity and forming a stable SEI, demonstrating its potential for high-performance LIB applications (Fig. 7B). Park *et al.*⁶⁵ developed a water-lily-seed-inspired silicon-carbon composite with void space (Si/void/AB/C) using a polymer coating method instead of hazardous chemical etching. Multiple Si particles were polymer-

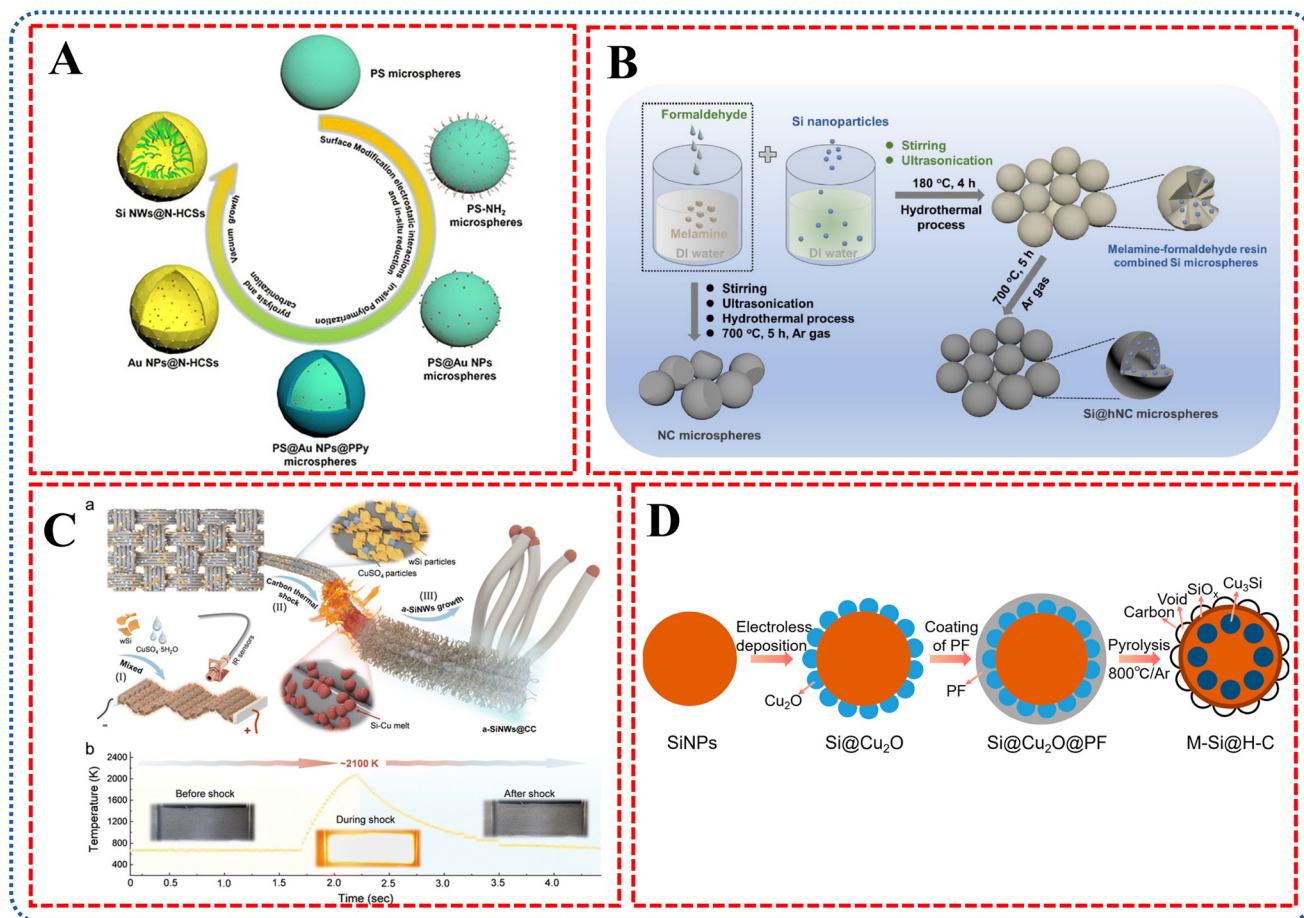


Fig. 6 (A) Diagram of the synthesis process of Si NWs@N-HCSs. (B) Schematic illustration of the synthesis of NC and Si@hNC MSs. (C) The CTS process for synthesizing a-SiNWs@CC. (a) Schematic diagram and (b) temperature profile and optical images of the carbon cloth substrate at different stages. (D) Schematic diagram showing the synthesis of M-Si@H-C. Adapted with permission from ref. 57–60. Copyright 2025@RSC; Copyright 2021@Elsevier; Copyright 2025@RSC; Copyright 2022@ACS.

coated to form a compact structure, with polymethyl methacrylate creating voids and acetylene black providing conductivity. The resulting anode demonstrated high reversible capacity over 400 cycles and high coulombic efficiency, offering a safer and scalable approach for industrial production of high-performance silicon-based LIB anodes (Fig. 7C). What's more, Wang *et al.*⁶⁶ investigated the effect of incorporating cerium (Ce) into the carbon coating of silicon-carbon composites (Si@C/CeO₂) for lithium-ion battery anodes. Ce incorporation enhanced the toughness of the carbon layer, reduced SEI formation, increased initial coulombic efficiency, and improved Li⁺ conductivity and rate capability. As a result, the composite achieved a high initial specific capacity of 1848.6 mAh g⁻¹ and maintained 502.2 mAh g⁻¹ after 180 cycles, demonstrating significantly improved electrochemical performance compared to conventional silicon-carbon composites (Fig. 7D).

4.3 Polymer and inorganic binders

Binders play a crucial role in maintaining electrode integrity, particularly for high-capacity silicon anodes. The adhesion

performance of polymer binders is strongly dependent on their chemical nature, the types of interfacial interactions they can form, and the properties of the active materials and conductive carbon additives.⁶⁷ For chemical systems undergoing large volume changes, polymer binders with strong yet reversible interactions are particularly essential to sustain structural integrity during repeated cycling.⁶⁸ Conventional poly(vinylidene fluoride) (PVDF) binders suffer from insufficient adhesion strength and mechanical flexibility, rendering them incapable of accommodating the severe volume changes of silicon. In contrast, advanced binders such as alginate, poly(acrylic acid) (PAA), and conductive polymers (*e.g.*, polyaniline and PEDOT:PSS) exhibit strong interactions with the hydroxyl-rich silicon surface through hydrogen bonding, esterification, or even covalent bonding.^{69,70} These interactions enable effective stress dissipation, prevent particle detachment, and in some cases provide self-healing capability to restore structural continuity after mechanical failure. Zhang *et al.*⁷¹ developed an aqueous hybrid gel binder for silicon anodes by cross-linking sodium carboxymethyl cellulose (NaCMC) with sodium

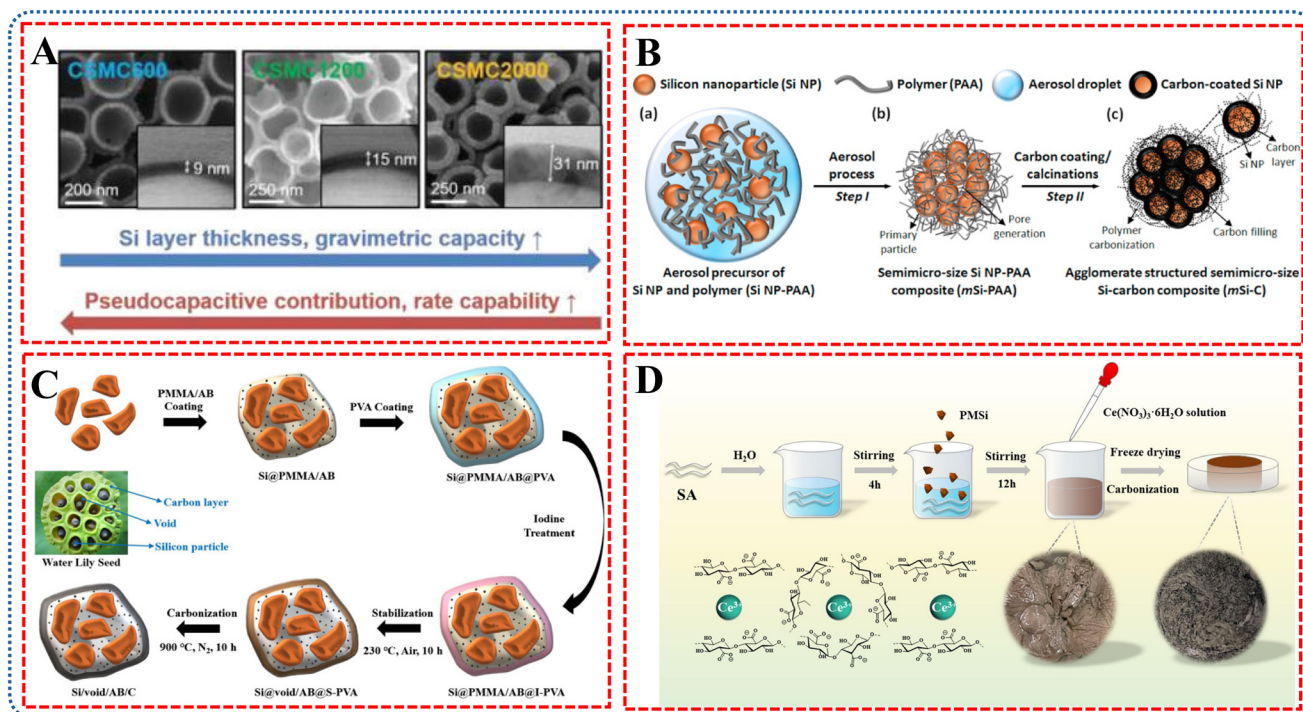


Fig. 7 (A) Schematic of the quantification of pseudocapacitive contribution in the nanocage-shaped silicon-carbon composite anode. (B) Formation process of the agglomerate structured semimicro-size silicon-carbon (mSi-C) composite. (a) Precursor solution of silicon nanoparticles and the polymer (PAA) for the aerosol process. (b) Superstructured composite of silicon nanoparticles and PAA (mSi-PAA) constructed by the aerosol process induced agglomeration. (c) Agglomerate structured silicon-carbon composite (mSi-C) after carbon coating/calcination. (C) Schematic illustration of Si/void/AB/C preparation and image of water lily seed. This illustration represents the cross-sectional images of the prepared materials for every step to demonstrate the structure of the material in detail. (D) Schematic of the synthesis of the Si@C/CeO₂ composite. Adapted with permission from ref. 63–66. Copyright 2019@Wiley; Copyright 2016@Elsevier; Copyright 2022@Springer; Copyright 2023@Elsevier.

borate. This crosslinked binder forms chemical bonds with Si nanoparticles while providing a deformable framework that maintains electrode integrity and buffers the >300% volume expansion of Si. As a result, the Si anode demonstrates excellent cycling stability (1211.5 mAh g⁻¹ after 600 cycles) and a high initial coulombic efficiency of 88.95%, highlighting the effectiveness of the binder design for improving Si-based LIB performance (Fig. 8A). Kim *et al.*⁷² synthesized a novel polyamide imidazole (PAID) binder with bifunctional groups that strongly interact with both Si particles and carbon black. The i-PAID structure provides π - π stacking for electrical conductivity and robust chemical binding to Si, effectively mitigating volume expansion and enabling higher reversible capacity and enhanced cycling stability compared to conventional polyimide binders (Fig. 8B). Inorganic binders, such as silicate or ceramic matrices, provide additional mechanical reinforcement but may compromise electrode flexibility. Wang *et al.*⁷³ developed a lithium metasilicate (LS) inorganic binder that forms strong adhesion with Si nanoparticles and provides Li⁺ transport channels. This design significantly improves cycling stability and rate performance, enabling high discharge capacities of 2123 mAh g⁻¹ (100 cycles, 0.84 A g⁻¹) and 663 mAh g⁻¹ at 8.4 A g⁻¹ (Fig. 8C). Ouyang *et al.*⁷⁴ introduced a functional binder for Si anodes that regulates the electric

double layer (EDL) structure and influences SEI formation at the molecular scale. The binder's strong Li⁺ affinity lowers desolvation energy by competing with solvent molecules, redistributing Li⁺ and reducing free solvent content, thereby suppressing excessive solvent reduction. As a result, an ultra-thin (11 nm) SEI with a robust inorganic inner layer and conductive organic outer layer is formed. This engineered interfacial chemistry enables excellent capacity retention and outstanding rate performance, offering new mechanistic insights and practical strategies for binder design in Si-based lithium-ion batteries (Fig. 8D). A rational binder design should carefully balance mechanical robustness, ionic and electronic conductivity, and chemical compatibility with the electrolyte, while also maintaining structural integrity during repeated charge-discharge cycles and minimizing undesirable side reactions that could compromise battery performance.

4.4 Artificial SEI and surface coatings

Artificial solid electrolyte interphase (SEI) engineering aims to create a stable and ionically conductive protective layer on the Si surface to suppress uncontrolled SEI formation during cycling. Techniques such as atomic layer deposition (ALD) and chemical vapor deposition (CVD) enable the formation of ultrathin coatings of Al₂O₃, TiO₂, or carbon layers, which act as

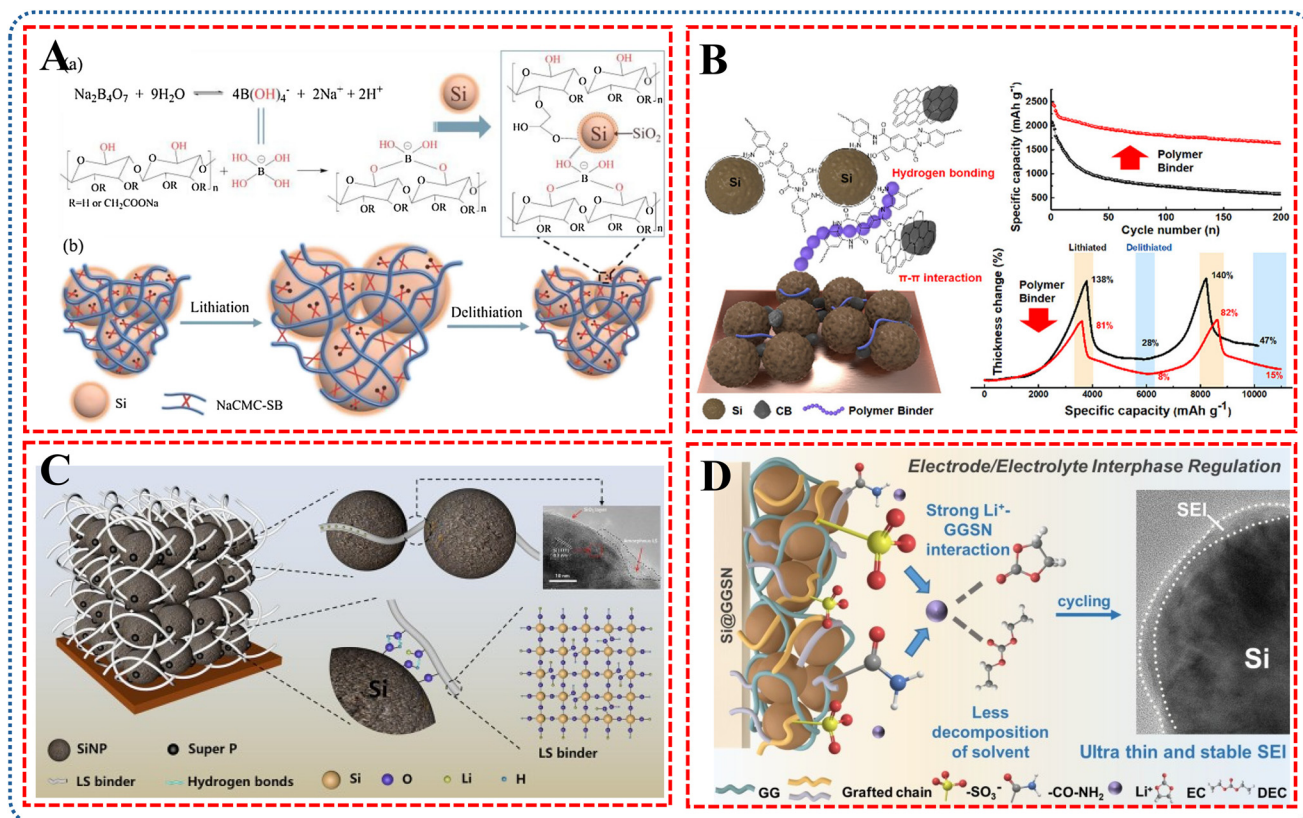


Fig. 8 (A) (a) The chemical structure and illustrative interaction between sodium carboxymethyl cellulose, sodium borate and silicon nanoparticles; (b) schematic of Si/NaCMC-SB configurations during the lithiation/delithiation process. (B) Schematic illustration of the ambidextrous polymeric binder for silicon anodes in lithium-ion batteries. (C) Schematic illustration of the Si anode with the LS binder. (D) Influence of binder functional groups on the Li^+ solvation structure at the interphase. Adapted with permission from ref. 71–74. Copyright 2018@Elsevier; Copyright 2022@ACS; Copyright 2023@Elsevier; Copyright 2025@Springer.

artificial SEI layers.⁷⁵ These coatings can effectively regulate Li^+ flux, prevent direct electrolyte decomposition, and reduce parasitic reactions. Reyes Jiménez *et al.*⁷⁶ investigated the effect of lithium phosphorus oxynitride (LIPON) coatings on Si thin film anodes, demonstrating that the artificial SEI layer effectively mitigates volume expansion and improves cycling stability and capacity retention. The LIPON coating also suppresses parasitic electrolyte decomposition, enhancing coulombic efficiency and overall electrode performance for potential microbattery applications (Fig. 9A). Mu *et al.*⁷⁷ developed an ~ 3 nm zinc oxide polymer coating *via* molecular layer deposition to stabilize the Si anode, achieving high capacity, excellent cycling stability, and superior rate capability. The *in situ* conversion of zinc oxide into a LiF-rich SEI enables fast ion/electron transport and robust structural integrity, with good compatibility in both carbonate- and ether-based electrolytes (Fig. 9B). Zhao *et al.*⁷⁸ developed a 2D/2D $\text{Ti}_3\text{C}_2\text{T}_x/\text{g}-\text{C}_3\text{N}_4$ composite to construct a stable artificial SEI on MXene for lithium metal anodes, enabling uniform Li plating/stripping and protecting against electrolyte corrosion. This design achieves high coulombic efficiency (98.4%), prolonged cycle life (>400 cycles), and improved full-cell performance with enhanced rate

capability and 85.5% capacity retention after 320 cycles (Fig. 9C). Additionally, electrolyte additives, including fluoroethylene carbonate (FEC), lithium bis(fluorosulfonyl)imide (LiFSI), and other fluoro-compounds, promote the formation of LiF-rich, mechanically robust SEI films with high ionic conductivity. Peng *et al.*⁷⁹ developed a LiFSI treatment strategy for prelithiated silicon anodes, forming a LiF-rich artificial SEI that reduces reactivity and enhances ionic conductivity. This approach improves initial coulombic efficiency (92.9%), cycling stability, and capacity retention, offering a promising route for high-energy-density silicon-based batteries (Fig. 9D). However, precise control over coating thickness and uniformity is essential, as overly thick layers can hinder Li^+ diffusion, while non-uniform coatings may fail under repeated cycling.

4.5 Advanced electrolytes and interfaces

The development of advanced electrolytes and interfaces is critical for stabilizing silicon anodes. Solid-state electrolytes (SSEs), including sulfide-based, oxide-based, and polymer-based systems, provide several advantages: they suppress dendrite growth, reduce electrolyte decomposition, and form

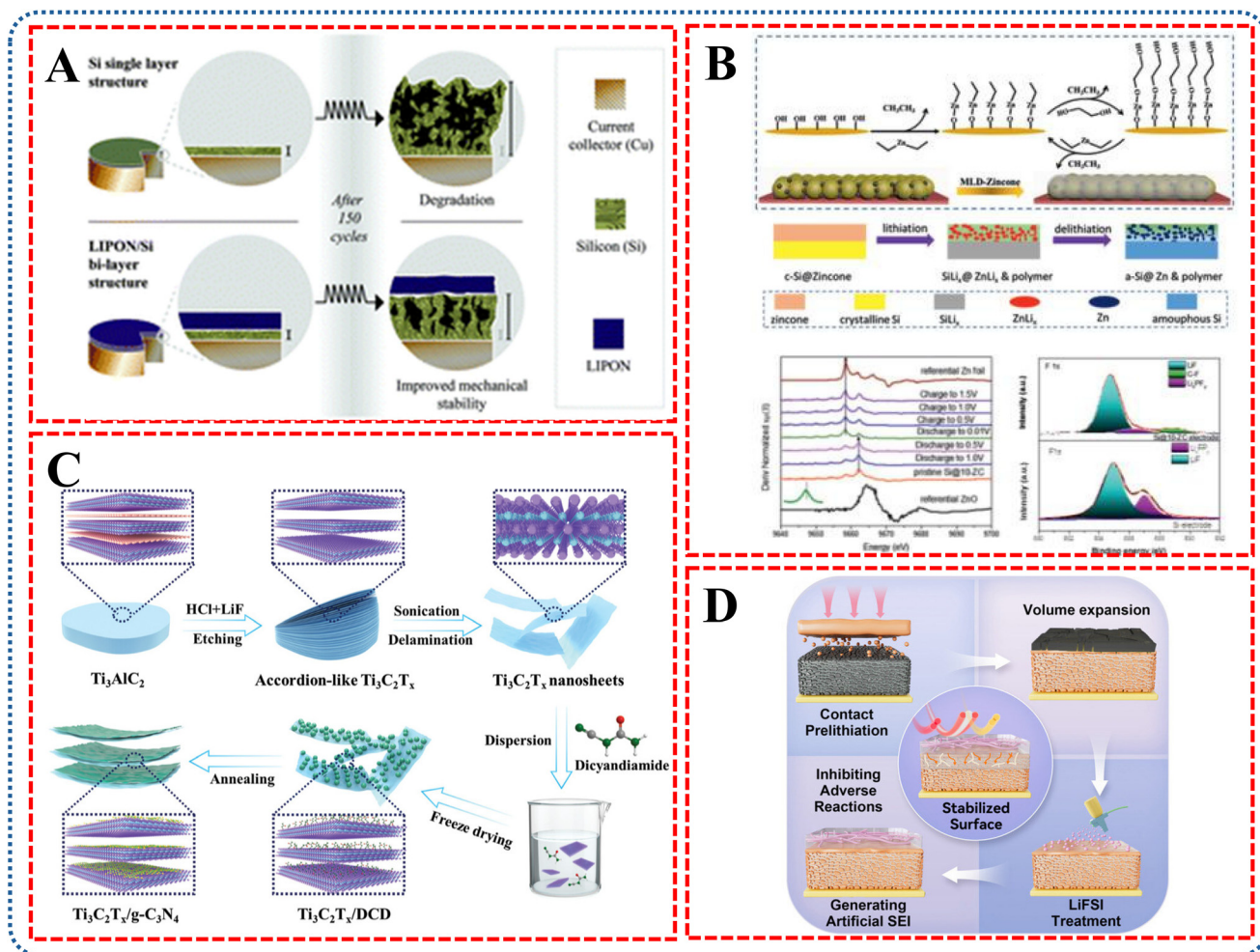


Fig. 9 (A) Schematic diagram of a step towards understanding the beneficial influence of a LIPON-based artificial SEI on silicon thin film anodes in lithium-ion batteries. (B) Schematic of stable silicon anodes with molecular layer deposited artificial zincine coatings. (C) Schematic illustration of the fabrication process of the $\text{Ti}_3\text{C}_2\text{T}_x/\text{g-C}_3\text{N}_4$ hybrid. (D) Schematic showing the LiFSI treatment process. Adapted with permission from ref. 76–79. Copyright 2018@RSC; Copyright 2021@Wiley; Copyright 2022@Wiley; Copyright 2025@MDPI.

stable interphases with Si.⁸⁰ Sulfide electrolytes offer high ionic conductivity and good interfacial contact but suffer from air/moisture sensitivity, whereas oxide SSEs provide better chemical stability at the expense of higher interfacial resistance.⁸¹ Polymer-based SSEs, particularly those incorporating flexible ionic channels, can accommodate Si's expansion while maintaining intimate interfacial contact.⁸² Tailoring the chemical composition and mechanical properties of these electrolytes, as well as introducing interface modifiers or gradient interphases, is key to enabling high-performance solid-state Si batteries. Wu *et al.*⁸³ employed a fluorine-rich carbon layer on silicon anodes to form a LiF-rich SEI, where semi-ionic fluorine promotes LiF nucleation, suppresses side reactions, and stabilizes the electrode interface. The resulting Si@C/F composite achieves high initial coulombic efficiency (88.8%), excellent long-term cycling (971.8 mAh g⁻¹ after 500 cycles at 1 A g⁻¹), and enhanced high-rate capability (Fig. 10A). Fang *et al.*⁸⁴ fabricated an ~5 nm Li₂O–lithicone laminated

film on silicon anodes *via* ALD/MLD, which provides an additional Li source, reinforces interfacial stability, and facilitates fast Li⁺ transport. The modified anode achieves high initial coulombic efficiency (91.2%), excellent rate performance (1460 mAh g⁻¹ at 2 A g⁻¹), and long-term cycling stability (>646 mAh g⁻¹ over 850 cycles) (Fig. 10B). Yan *et al.*⁸⁵ developed a surface-selective electrocatalysis strategy using 1T-MoS₂ with sulfur vacancies to construct an ultra-dense, robust fluoride-rich SEI on silicon anodes. The Si@MS electrode exhibits excellent cycling performance with 95.5% capacity retention and >99.8% average coulombic efficiency over 1000 cycles at 1 A g⁻¹ (Fig. 10C). Liu *et al.*⁸⁶ designed a multifunctional quasi-solid gel polymer electrolyte (QSGPE) that forms a “breathing” 3D elastic Li⁺-conducting framework, reinforcing Si anode structure and stabilizing the interface. This approach enables high initial coulombic efficiencies (>88%) and excellent cycling stability for Si anodes, with NCM811||Si cells retaining ~82% capacity after 100 cycles at 0.5 A g⁻¹ (Fig. 10D).

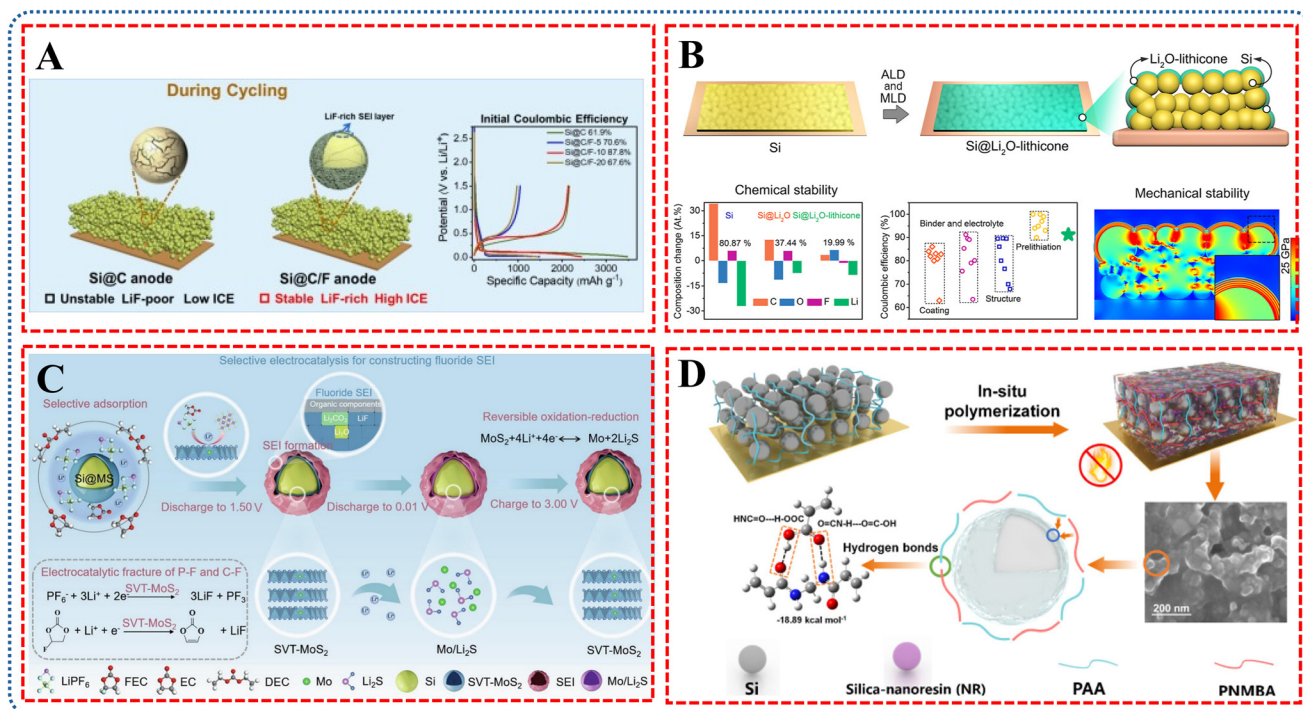


Fig. 10 (A) Schematic of the LiF-rich solid electrolyte interface induced by fluorinated carbon enabling stable silicon anodes with high initial coulombic efficiency. (B) Schematic of atomic/molecular layer-deposited laminated Li_2O -lithicone interfaces enabling high-performance silicon anodes. (C) Schematic of surface selective electrocatalysis-derived ultra-dense and mechanically robust fluorinated solid electrolyte interface for high-capacity and long-cycling silicon electrodes. (D) Curing process of the quasisolid gel polymer electrolyte (QSGPE) and the changes in the internal components of the electrode before and after *in situ* polymerization. Adapted with permission from ref. 83–86. Copyright 2025@Elsevier; Copyright 2023@ACS; Copyright 2025@Elsevier; Copyright 2024@ACS.

5. Commercialization and industrial perspective: materials and manufacturing strategies for industrial adoption

5.1 Materials and process strategy for industrial adoption: a low-SSA, dense, thin-coated practical platform with targeted upgrades

Industrial adoption of silicon-based anodes hinges on optimizing the entire chain—from material selection through slurry/coating, formation, and line integration—under the constraints of Throughput-Yield-\$ per kWh-EHS. For mainstream EVs, the prevailing baseline is a conservative route that steadily blends low loadings of silicon-family materials into a graphite backbone (Si-equivalent <10 wt%). Here, “silicon-family materials” primarily denote SiO_x -C composites and carbon-encapsulated or carbon-composited low-SSA micron Si (Si@C), which dominate current commercial practice. We use “Si-equivalent” to refer to the silicon mass fraction in composite systems such as SiO_x . This choice directly reflects industrial realities around managing initial coulombic efficiency (ICE) losses, large volume change, and electrode density/polarization limits amidst real line variability.^{44–47}

On the synthesis and post-processing side, the field converges on micron/metallurgical-grade Si with uniform hybrid coatings (~ 5 –50 nm) as the baseline, controlling ICE, resistance, and gas evolution; nano-Si is added only selectively where the performance dividend justifies the cost. Two complementary upgrade paths are being refined for industry: (i) depositing ultra-thin/nanolaminar a-Si from silane (SiH_4) or related precursors onto carbon backbones (graphite, CNTs, 3D graphene, porous hard carbon), thereby stacking silicon on a continuous electronic network; and (ii) conformally coating porous-Si frameworks with carbon to construct core-shell or yolk-shell architectures, where internal voids accommodate expansion and the carbon shell moderates electrolyte exposure. The first path favors high tap density and electrical continuity; the second excels at expansion buffering and SEI stabilization. Both, however, entail trade-offs—EHS/cost for SiH_4 and low-temperature CVD in (i), and shell-thickness/density/ion-transport compromises in (ii)—that must be judged against the segment-specific acceptance window.^{44–47,87}

At the electrode level, graphite-silicon-family composites remain the pragmatic axis. Blending low-SSA micron Si@C or SiO_x -C with graphite/carbon black to establish the primary percolation network, and then densifying by calendaring while maintaining a porosity window of roughly 20–35%, suppresses the polarization rise otherwise caused by thickness. Small

additions of CNTs/VGCF extend long-range electronic pathways, stabilizing sheet resistance and dispersion in thick electrodes. Graded secondary particles (micro-pores at the skin, meso-pores in the bulk) absorb expansion without sacrificing tap density, while thin carbon coatings (pitch/resin-derived or thin CVD/sol-gel carbons) and optional ultrathin inorganic nano-coatings (e.g., Al_2O_3 and TiO_2) in hybrid stacks promote compliant, LiF-rich SEI layers with good reproducibility. For the binder/conductive framework, mixed aqueous systems—CMC/SBR combined with ionic/crosslinkable components such as PAA or alginate—serve as the default, and multi-scale conductive networks (carbon black for local contacts, graphite for bulk conduction, CNT/VGCF for long-range pathways) offer robustness to high-solids (≥ 60 –70 wt%) and thick-electrode processing variability.

Interface/electrolyte packages can be co-designed with formation to simultaneously optimize ICE, gas evolution, and impedance: FEC/VC; F-rich SEI promoters such as LiPO_2F_2 /DFOB; LiFSI salts with appropriate stabilization; LHCEs built around donor-number-guided diluent selection; and roll-to-roll-compatible artificial-SEI primers. When paired with low-current, multi-step CC/CV formation including dwell periods and with tuned temperature/stack pressure, these packages achieve better early-cycle stability and lower scattering.^{88–93} Finally, pre-lithiation remains a lever for immediate energy-density gain by compensating initial Li loss, but it carries costs in residues/gas, uniformity, line complexity, and certification/safety. Segment-appropriate adoption should therefore be decided by the combined metric of dosing precision $\times$ uniformity $\times$ by-product control $\times$ line compatibility.^{94,95}

5.2 Industrial pathways and market outlook (2025–2035): acceptance windows and case studies (with Si-family clarity)

The co-designed package defined in section 5.1—low-SSA, dense, thin-coated materials together with a composite-electrode architecture, interface/electrolyte engineering, and pre-lithiation—maps the acceptance window along throughput-yield-\$ per kWh-EHS. Within this frame, a three-stage trajectory is anticipated for 2025–2035. First, mainstream EVs continue on a conservative route that stably blends low levels of silicon-family material into graphite backbones (<10 wt% Si-equivalent), predominantly SiO_x -C and low-SSA micron Si@C; broad commercialization of neat Si metal or stand-alone nano-Si electrodes has not yet been substantiated. Second, in segments with a high performance dividend (long-range driving, ultra-fast charging), mid-range loadings (10–30 wt% Si-equivalent) expand selectively—still centered on low-SSA micron Si@C, pitch/polymer-carbonized encapsulated Si-C, and higher-Si SiO_x -C recipes. Third, high-silicon (>30 wt% Si-equivalent) and nano-structured Si-C (nanowires, porous Si@C, yolk-shell) continue to build trust in premium niches such as aviation/UAV and may enter EVs conditionally as formation/interface/electrolyte maturity and line compatibility improve. Even in this stage, industrial consensus maintains that carbon-composite/encapsulated formats are the practical premise.^{94,95}

Case studies illustrate the continuum. Tesla's large cylindrical cells have progressively migrated from graphite to graphite with silicon-family blends, leveraging low-cost Si sources with polymer coatings/binders within line-compatibility limits. Amprius has demonstrated high gravimetric and volumetric energy densities with nanowire Si-C first in aviation/UAV, exemplifying the “niche-first $\rightarrow$ scale-out” adoption pattern. Sila's nano-composite Si and Group14's high-silicon Si-C are scaling *via* OEM partnerships and capacity build-outs, and across these programs, a shared lesson is clear: co-designing electrolyte/formation packages with pre-lithiation is pivotal for yield and storage stability.^{94,95}

5.3 Regional strategies and collaboration: Korea (Daejeon), Japan, China, the United States, and the EU

Region-specific ecosystems implement the 5.1 package according to local regulation, cost structures, and market positioning, yet converge on the same core principle: a low-SSA, dense, coated baseline combined with graphite-silicon-family composites, interface/electrolyte engineering, and pre-lithiation. Korea is distinguished by production-grade alignment of SiO_x -C; notably, Daejeon Electronic Materials foregrounds SiO_x -based anodes positioned for aqueous, high-solids processing. Its joint development with Epsilon Advanced Materials on graphite-rich Si composites (targeting ~ 450 –600 mAh g^{-1}) underscores a staged roadmap from low Si-equivalent blending to mid-range loadings. This approach blends Korea's strength in yield/EHS-oriented line alignment with global partnerships to broaden adoption in mainstream EVs.^{93,96,97}

Japan leverages long-standing advantages in cell manufacturing, specialty materials, and standards. Panasonic Energy's announcement of mass production of 4680-format automotive cells signals a push toward higher energy densities, while procurement of silicon-family anode materials from external suppliers (e.g., Nexeon) indicates readiness for next-generation recipes. In parallel, ZEON is expanding global capacity in aqueous SBR binders, raising industrial baselines for rheology and adhesion under thick-electrode/high-solids conditions. In short, Japan is advancing *via* the triad of form-factor innovation (4680) $\times$ Si-family supply-chain build-out $\times$ standardized binder/functional-layer processing, all oriented toward line compatibility.^{44,98–101}

China's scale and vertically/horizontally integrated value chains enable rapid insertion of SiO_x /Si-C into thick, high-tap-density electrodes and accelerated field optimization of electrolyte/additive packages for ultra-fast charging ecosystems. The United States pursues a stepwise strategy in which high-silicon/nano-structured Si-C suppliers (Amprius, Sila, Group14) gather performance and reliability evidence in aviation/premium EVs with OEM partners before broader EV roll-out. The EU's battery-passport and sustainability regulations raise standardized requirements for carbon footprint, recyclability, and traceability, thereby reinforcing documentation of process changes (MoC) and manufacturing readiness levels (MRLs) in electrolytes and formation blocks. Across regions,

the vectors differ, but they all instantiate the 5.1 package in region-appropriate ways.^{94–96,102,103}

5.4 Standardization and industrial road-mapping: aligning KPIs, test methods, and gating

Translating the 5.1 package into production demands a single, connected design space spanning KPIs, test methods, TRL/MRL gates, and EHS/sustainability. Electrochemical KPIs include ICE and retention across 25–60 °C, impedance growth, rate/low-temperature performance, and storage stability. At the electrode level, tap density and porosity (≈ 20 –35%), thickness-dependent resistance, and cyclic expansion/recovery must be controlled in tandem. On the process side, reproducible high-solids rheology, robust drying/calendering windows, and control of defect modes (delamination, cracking, pinholes) govern yield sensitivity.^{88–90,98}

A practical test regime couples a formation-protocol matrix (low-current, multi-step CC/CV with dwell; temperature and stack-pressure design-of-experiments), *in situ* gas/expansion measurements, electrolyte screening (FEC/VC, LiPO₂F₂/DFOB, LiFSI; LHCEs designed by diluent donor number), and combination tests of binder-conductive frameworks-artificial SEI. The contributions of artificial SEI primers should be systematically integrated with electrolyte and formation protocols to mitigate early-stage variability and concurrently improve ICE and gas evolution.^{85–93,97}

Pre-production qualification should be formalized as TRL/MRL gating. TRL upgrades (coin $\rightarrow$ pouch $\rightarrow$ large formats) must pass fixed criteria for ICE, lifetime, and stability, while MRLs should codify process capability (Cpk) and management of change (MoC) across slurry-coating-drying-calendering-pre-lithiation-formation. Sustainability documentation—battery passport, solvent-recovery yields, dust collection/explosion protection/off-gas scrubbing, hazard assessments for LiFSI/additives, scrap routing and recyclability, and carbon-footprint accounting—must be tracked with data. Japan's standardization of binders/functional layers (*e.g.*, ZEON's aqueous portfolio expansion) and Korea's line alignment around SiO_x-C (*e.g.*, Daejoo) together with regulatory frameworks in the U. S./EU can catalyze international alignment of KPI-test-gate systems.^{47–50,88–90,96–98,101}

6. Future directions and outlook

6.1 Integration with next-generation systems

Silicon anodes are expected to play a pivotal role in solid-state batteries (SSBs) and lithium-sulfur (Li-S) and lithium-air (Li-O₂) systems, where their high capacity can synergistically boost the energy density beyond the limits of conventional lithium-ion batteries (LIBs). In solid-state configurations, the use of inorganic (sulfide/oxide) or polymer electrolytes can effectively suppress continuous SEI growth and improve thermal stability, while tailored interfacial engineering may enable stable Si-electrolyte contact under large volume changes. Zhang *et al.*¹⁰⁴ developed a 3D Sn-Ni metallic framework *via* an inorganic gel-

reduction method to serve as a conductive and buffering matrix for Si anodes. The resulting Ni framework exhibited excellent structural integrity and synergistic lithium-storage behavior, delivering 1205 mAh g⁻¹ after 100 cycles and 653 mAh g⁻¹ at 10 A g⁻¹ (Fig. 11A). In Li-S and Li-air systems, silicon can serve as a hybrid anode or act as a polysulfide/polysuperoxide anchor, potentially mitigating shuttle effects and stabilizing the interface. Baasner *et al.*¹⁰⁵ reported a silicon-carbon composite anode for lithium-sulfur batteries, where a sulfur-templated void structure (Si@void@C) accommodates silicon's volume changes, enabling stable lithiation over 50 cycles. In full cells, the prelithiated Si-C anode paired with a sulfur cathode achieved high capacity (807 mAh g⁻¹ sulfur⁻¹) with minimal lithium excess (76%), demonstrating enhanced energy density and safety (Fig. 11B).

6.2 Sustainable/green synthesis strategies

Future research will increasingly emphasize eco-friendly and cost-effective fabrication methods, including the use of abundant precursors (*e.g.*, rice husk-derived SiO₂ and metallurgical-grade Si), solvent-free processing, and low-temperature reduction techniques. Green synthesis approaches, such as mechanochemical milling, bio-derived carbon coatings, and water-based binder systems, will help reduce the carbon footprint of Si anode manufacturing while maintaining or enhancing electrochemical performance. Zhang *et al.*¹⁰⁶ developed a green and effective strategy to convert photovoltaic silicon waste (PVSi) into high-performance lithium-ion battery anodes using a hot-pressing method with PVSi, asphalts, and graphite. The resulting PVSi@C/G-1 anode exhibits excellent cycling stability and rate performance, achieving capacities of 906 mAh g⁻¹ after 500 cycles and 899 mAh g⁻¹ after 900 cycles, while avoiding secondary environmental pollution. Recycling and reusability strategies, including closed-loop recovery of Si particles from end-of-life batteries, will also become critical to achieving sustainable silicon anode production (Fig. 12A). Sathiyamoorthy *et al.*¹⁰⁷ reported a sustainable approach to recycle silicon kerf slurry waste by converting it into silicon-graphite composite anodes for lithium-ion batteries. The resulting Si-Gr anode exhibits high crystallinity, homogeneous particle dispersion, and excellent electrochemical performance, achieving a discharge capacity of 1434 mAh g⁻¹ after 100 cycles at 100 mA g⁻¹ (Fig. 12B).

6.3 Bridging the academic-industrial gap

Although substantial progress has been achieved at the laboratory scale, significant challenges remain in translating silicon anode technologies into industrial production with competitive cost, yield, and reliability. A key limitation lies in the mismatch between academic performance metrics and industrial requirements. While many studies emphasize high specific capacity and long cycle life in half-cell configurations, industrial deployment requires strict control over areal capacity, electrode density, swelling behavior, initial coulombic efficiency (ICE), and compatibility with existing manufacturing processes.

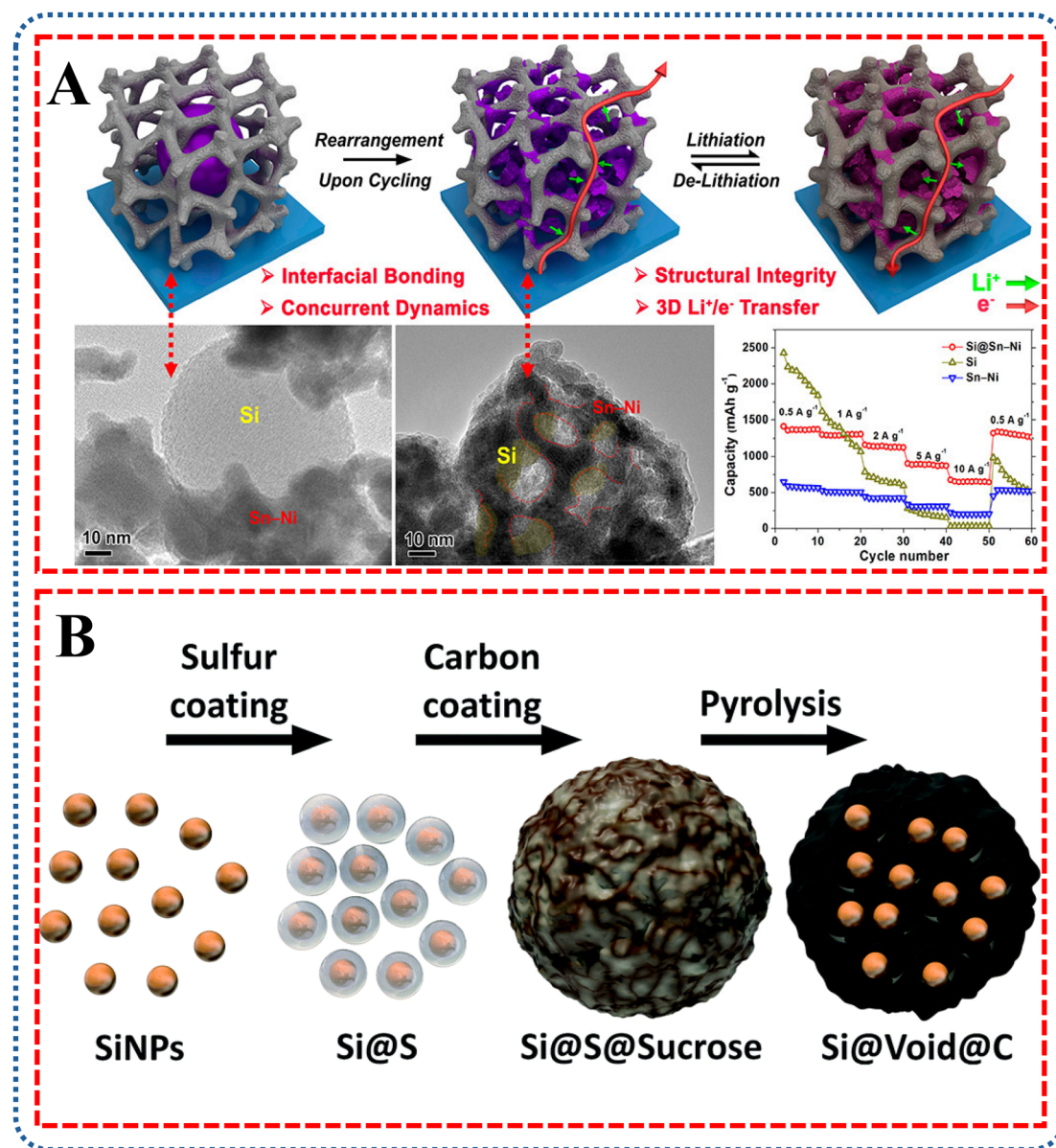


Fig. 11 (A) Inorganic gel-derived metallic frameworks enabling high-performance silicon anodes. (B) Schematic illustration of the synthesis process of the nanostructured silicon-carbon composite (Si@void@C). Adapted with permission from ref. 104 and 105. Copyright 2019@ACS; Copyright 2018@RSC.

In particular, nanostructuring strategies, although effective in mitigating volume expansion, often suffer from low tap density and high fabrication cost, limiting their practical applicability. In addition, advanced interfacial engineering approaches may introduce complexity in large-scale processing and reproducibility. Therefore, bridging this gap requires a transition from performance-oriented material design to manufacturability-driven optimization. This includes the development of scalable composite architectures (*e.g.*, graphite-Si systems), industrially viable prelithiation strategies, and electrolyte formulations compatible with high-loading electrodes. Close collaboration among academia, cell manufacturers, and material suppliers will be essential to align material inno-

vation with process integration and commercialization requirements.

6.4 Prediction: when and how silicon anodes will dominate the LIB market

Given the rapid advancements in composite anode technologies and increasing demand for high-energy-density batteries in electric vehicles (EVs), wearable electronics, and grid storage, silicon is projected to gradually replace a significant portion of graphite anodes within the next 5–10 years. Initial adoption will likely focus on graphite-Si hybrid anodes with 5–30 wt% Si content, followed by high-loading (>70 wt%) Si composite or full-Si anodes in solid-state batteries around

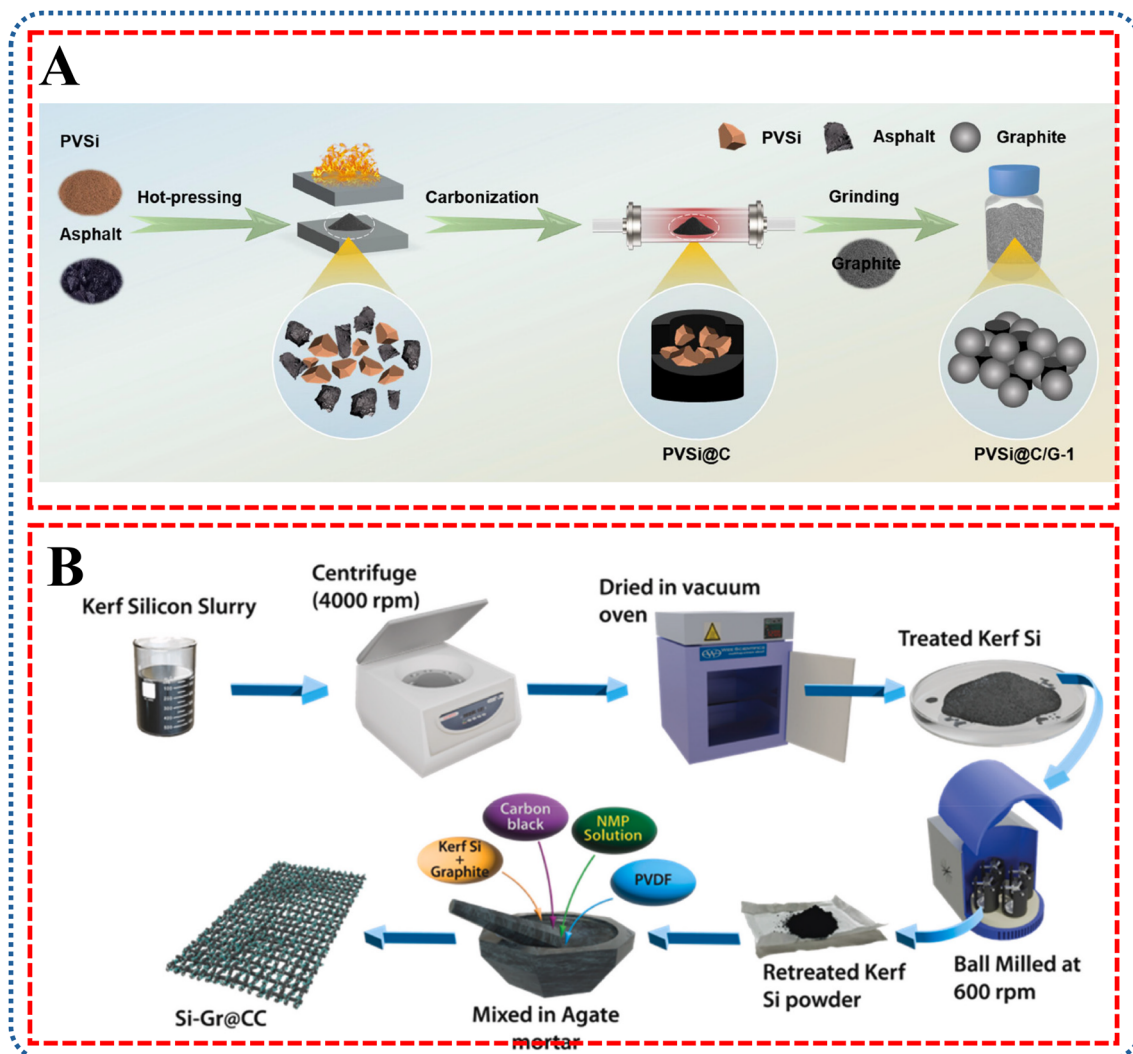


Fig. 12 (A) Diagrammatic representation of the PVSi@C/G synthesis processes. (B) Schematic diagram illustrating the Si kerr slurry waste treatment to synthesize Si-Gr nanocomposite coated carbon cloth as the anode for LIBs. Adapted with permission from ref. 101 and 102. Copyright 2025@ACS; Copyright 2025@ Elsevier.

2035, driven by the maturation of interface stabilization techniques and cost reductions in nanosilicon production. Complete dominance of Si anodes over graphite may not occur until beyond 2040, when both technological and supply-chain bottlenecks are sufficiently addressed.

7. Conclusion

Silicon anodes, owing to their exceptionally high theoretical capacity, natural abundance, and potential safety advantages over graphite, have emerged as one of the most promising candidates for next-generation lithium-ion batteries. However, their practical application remains hindered by critical challenges, including severe volume expansion, mechanical pulverization, unstable solid electrolyte interphase (SEI), and low initial coulombic efficiency. Significant progress has been

achieved through nanoscale engineering, silicon-carbon composite design, conductive coatings, and advanced binders, which collectively improve structural integrity and cycling stability. Meanwhile, interface and electrolyte engineering strategies have further mitigated interfacial degradation and enhanced electrochemical stability. From an industrial perspective, advances in scalable synthesis, practical composite architectures, and compatible electrode fabrication processes are accelerating the early-stage commercialization of silicon-based anodes. Nevertheless, key challenges such as pre-lithiation and cost-effective large-scale manufacturing remain to be addressed. Looking forward, silicon anodes are expected to serve as a critical bridge between current graphite-based systems and emerging battery technologies, including solid-state, lithium-sulfur, and lithium-air batteries. Continued synergy between fundamental research and industrial development will be essential to unlock their full potential. Overall,

silicon anodes represent a transitional yet transformative technology, offering a viable pathway toward higher energy density while enabling new materials design paradigms for next-generation energy storage systems.

Author contributions

Xiong Cheng: conceptualization, investigation, validation, and writing the original draft. Heonsoo Park: funding acquisition and writing & editing. Joonho Bae: supervision, funding acquisition, and writing & editing.

Conflicts of interest

The authors declared that they have no conflicts of interest to this work.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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