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Nano-Engineered Materials for Overcoming Energy Density Barriers in Electric Vehicle Batteries

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Abstract. The development of electric vehicles (EVs) is highly dependent on the advancement of high-energy-density battery technology, as this directly determines the range, charging efficiency, and overall performance of EVs. However, current battery systems still have significant limitations: the instability of materials (such as the structural collapse of electrode materials during charging and discharging cycles) and interface issues (including poor ion transport and interface side reactions) severely restrict their practical application. This paper systematically reviews strategies based on nanotechnology, aiming to overcome these key obstacles, with a focus on the design and application of new nanomaterials and nanostructures in the field of materials chemistry. The key findings of the reviewed studies include: nano-coatings (such as oxide films) and element doping of high-nickel electrodes significantly improve structural stability and inhibit capacity degradation; silicon-based nanomaterials effectively alleviate the severe volume expansion of anode materials, thereby improving cycle life. In addition, artificially constructed interface layers (such as solid electrolyte interface layers) can optimize ion selectivity and enhance mechanical durability, while thick electrodes combined with nanoscale conductive networks (such as carbon nanotubes) can promote efficient charge transfer and increase energy density without reducing rate performance. Overall, these methods driven by nanotechnology not only increase the energy density of EV batteries but also ensure excellent cycle performance and safety. This research further emphasizes the crucial and irreplaceable role of nanotechnology in driving the innovation and development of next-generation high-performance EV battery technologies.

Keywords: Nanostructured Cathodes, Silicon Anodes, Artificial Interphases, Thick-electrode Architecture, Energy Density

1. Introduction

In recent years, the development of new energy vehicles has been rapid. The development of new energy vehicles relies on batteries with high energy density. The energy density of the battery pack is approximately 70-120 Wh/kg [1]. However, to achieve a driving range of 500 kilometers, the energy density of the battery pack must reach about 300 Wh/kg [2]. Due to the particularity of lithium-sulfur batteries for small electric vehicles, the volumetric energy density (Wh/L) remains a significant challenge in practical applications. Therefore, it is necessary to enhance the energy

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density and volumetric energy density of batteries [3]. However, the work will just explain the energy density barriers in electric vehicle batteries. In the field of batteries, achieving high energy density remains a challenge because traditional current collectors, due to their inability to allow the electrolytes, hinder the movement of lithium ions and limit the performance of thick electrodes, thereby restricting the energy density [3].

Battery aging refers to the degradation that occurs during use or storage [4]. It is mainly manifested as a decrease in the battery's energy density and output power [4]. The cycle number refers to how many times a battery completes the charging and discharging process at a specific depth of discharge [5]. The completion of one charging and discharging process is regarded as one cycle [4]. Nanotechnology is a great way to resolve this energy density problem.

The instability of the material, the instability of the interface, and the transmission problem of the thick electrode are the challenges to the energy density of the battery [4, 5]. Within the temperature range of 20 to 70 °C, the rate of aging continuously changes, indicating that lithium-ion batteries are not stable under such external temperature conditions [6]. This reflects the instability of the materials [6]. A major issue is battery interface failure caused by the expansion of silicon-based electrodes, which can expand up to 300%, leading to particle shedding [7]. Another issue is related to thick electrodes in lithium-ion rechargeable batteries, where the loading level of the cathode active material coated on each square centimeter of the electrode sheet is 28 milligrams. After long-term cycling tests [8]. Increased resistance reduces charge transfer efficiency, which lowers capacity and consequently decreases energy density [8]. Thick electrodes refer to increasing the amount of active material in the electrode to directly enhance energy density [9]. However, they also suffer from reduced penetration depth, which in turn deteriorates battery performance [9].

Since much of the existing research is comprehensive, this work focuses on: (1) How to stabilize the high-nickel cathode through surface/substrate nanoengineering without sacrificing the redox activity? (2) What kind of nanostructure enables silicon to maintain high specific capacity while achieving sustainable mechanical integrity? (3) What kind of nano-porous/porous-flow framework in thick electrodes can enhance the utilization of electrolyte and reduce polarization?

The entire text is centered around three main threads of nanotechnology. First, this work addresses the issue of interfacial side reactions in high-nickel layered cathodes. Then it explains how doping alleviates this problem and clarifies how nanomaterials optimize the high-nickel electrode. Second, it discusses the structural design of silicon and the issue of silicon volume expansion, which leads to the cracking of the SEI, and how nanotechnology can alleviate this problem through structural design. Finally, it explained how nanomaterials improved the efficiency of the electrolyte by constructing 3D conductive frameworks in thick electrodes

2. Literature review

2.1. Chemistry-centred nano-engineering

2.1.1. Nanoscale coating/doping for high-nickel layered cathodes

The high-nickel layered cathode family typically contains ≥80% Ni in the transition-metal layer (e.g., NMC811/NCA) [10, 11]. Such chemistries dominate state-of-the-art EV lithium-ion cells [10]. $LiNiO_2$ can reversibly deliver a higher specific capacity than $LiCoO_2$ within the same operating voltage range [10].

However, there are some significant disadvantages to consider. The structure of high-nickel layered cathodes is unstable, which is one of the vital disadvantages. The ideal structure of high-

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nickel materials is the O_3-type hexagonal structure, which consists of alternating layers of lithium ions (Li^+) and transition metal layers (such as Ni, Co, and Mn), with oxygen atoms forming a framework in close-packed slabs [12]. Because Ni^{2+} (ionic radius) is similar to Li^+, and Ni^{3+} can readily reduce to Ni^{2+} during synthesis, Ni^{2+} can occupy Li-layer sites, causing the lithium/nickel cation intermixing (Ni/Li disorder) [12, 13]. The Ni/Li disorder can block Li-ion diffusion pathways, restricting the transport of lithium ions, leading to poorer rate capability and reduced cycle life [14]. Moreover, residual, highly reactive surface lithium species can react with ambient CO_2/H_2O to form Li_2CO_3/LiOH, consuming cyclable lithium, and thereby lowering capacity. Therefore, this is a harmful side reaction. In addition, when the charging voltage is too high, the lattice oxygen structure becomes unstable, and lattice oxygen loss (O_2 release) can occur. The reduction of lattice oxygen leads to the rearrangement of the remaining metal atoms into a dense rock-salt phase. This structure makes it difficult for lithium ions to pass through, so the cyclable lithium decreases over time, and the energy density drops accordingly [11].

Conformal nanoscale surface coatings act as protective interphases at particle/electrolyte interfaces and markedly enhance high-Ni cathode durability. Theoretically, the cathode can be coated with stable electrolyte-resistant compounds to enhance cycle stability. For instance, TiO_2 and SiO_2 are widely used nanocoatings; TiO_2 is chemically robust and mechanically resilient. This layer effectively separates the electrolyte from the active surface, preventing harmful side reactions. After 500 charge-discharge cycles, the TiO_2-coated cathode retained 72.2% of its initial capacity. Moreover, SiO_2, which is cost-effective and environmentally friendly, also protects the surface and suppresses transition-metal dissolution into the electrolyte [11].

2.1.2. Nanocomposite design for silicon-based anodes

Silicon has attracted increasing attention due to its numerous attractive properties, such as a theoretical specific capacity of up to 4212 mAh/g (1685 Wh/kg), which is much higher than graphite [5].

Nevertheless, there is a severe issue with silicon-based anodes: the extremely large volume expansion (>300%) [7]. During lithiation/delithiation, Li-Si alloying drives >300% volumetric change, causing particle fracture, electrical disconnection, and structural failure [7].

There are two nanostructuring strategies to relieve this volume-expansion problem. The first strategy is hollow nanosilicon spheres [5, 7]. The hollow structure provides space for expansion, preserving particle integrity [5]. The electrode material consists of encapsulated hollow 5-nanometer-sized polymeric silicon nanoparticles. At a current density of 0.25 A/g, this electrode has an energy density of 628 Wh/kg, and after 250 discharge-charging cycles, the battery energy density is 65% of its initial value [15]. Figure 1 is an effect of this method [7].

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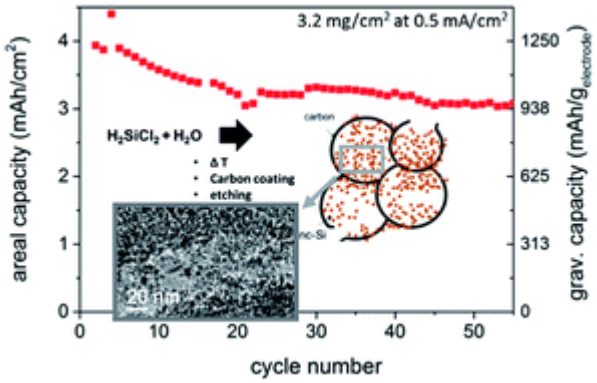

Figure 1. Schematic of a hollow nano-Si sphere and the energy density of batteries [15]

The second strategy is silicon nanotubes/nanowires. Silicon nanotubes have a large specific surface area and high axial freedom, providing high flexibility [7, 16]. They accommodate radial expansion with reduced stress concentration, mitigating inter-particle compression and pulverisation [16]. Figure 2 simply illustrates the structure of these nanotubes [16]. Ultimately, Si nanowire electrodes demonstrated a reversible capacity of up to 1277.2 Wh/kg [7].

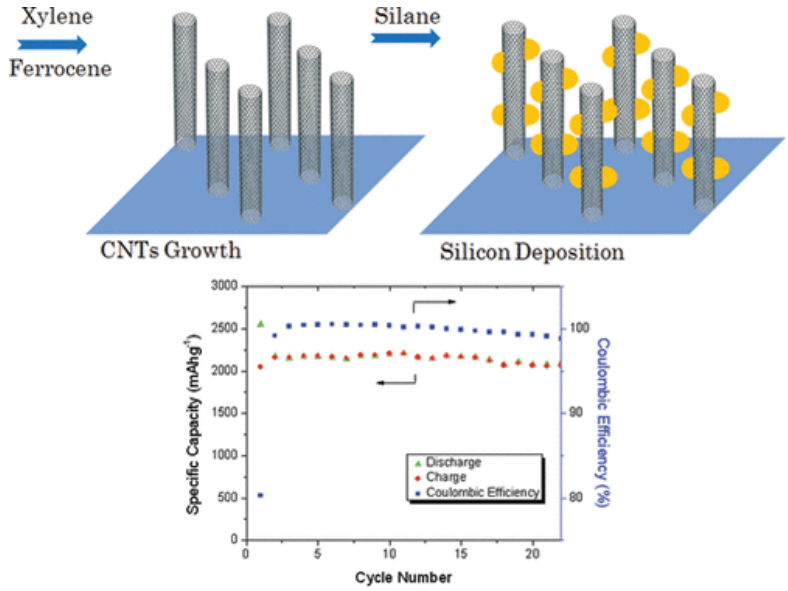

Figure 2. The principle of hollow silicon nanotubes in Li-ion cell [16]

2.2. Interface/architecture-centred nano-engineering

2.2.1. The core role of nanotechnology in artificial SEI

The natural SEI is formed during the discharge and charging processes of the battery [17]. Therefore, this SEI has many drawbacks, such as unstable performance, uneven structure, and low ionic conductivity etc. [17]. These problems will also indirectly lead to a decrease in battery energy density [18]. To solve these problems, it is necessary to artificially create an artificial SEI that can simultaneously achieve ionic conduction, electron blocking, and mechanical buffering functions to replace the natural SEI [17, 18].

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Through the ingenious design of nanostructures, the artificial SEI can possess both the key functions of interface selectivity and mechanical properties. To achieve electronic blocking, the band gap of the material is generally very large. For example, in LiF, the band gap is as high as 13.6 eV. The band gap is a measure of the minimum energy required for an electron to be excited from the valence band to the conduction band. Therefore, the higher the band gap, the less conductive the material is [18].

To achieve the purpose of blocking electrons but allowing ions to pass through, ordinary electronic insulators are not suitable [17]. Because many electronic insulators are also ionic insulators, anyway, this difficulty can be overcome through nanoscale materials [18]. By turning the material into a thin coating at the nanoscale, lithium ions may be able to migrate through the extremely thin barrier [18]. Another composite structure can also effectively solve this problem [18]. For example, nano-sized particles of LiF provide the function of blocking electrons through their wide bandgap characteristics, and combined with some polymer electrolytes such as PEO, they can provide a channel for ion transmission [18]. The impact of such a structural design is that the wide-bandgap inorganic nanoparticles block electrons, while lithium ions can migrate rapidly through the polymer [18]. Thus, the artificial SEI perfectly fulfills both the functions of electron blocking and ion channeling [17].

2.2.2. Thick electrode architectures with nanoconductive networks and gradient porosity

Thickening the electrode is a common way to increase the energy density of batteries [19]. However, thickening the electrode brings about three problems: ion transport limitation, electron transport limitation, and mechanical instability [9]. As the thickness of the electrode increases, the time it takes for ions to reach the deepest part is proportional to L^2. Doubling the electrode thickness will further prolong the diffusion time, resulting in extremely fast battery reaction speed and preventing lithium ions from being replenished in time within the battery [9]. Thick electrodes will cause electrons to travel a longer distance and have more contact points with particles [19]. Each contact point has resistance, ultimately resulting in an uneven utilization of active materials and a decrease in battery capacity [9]. Moreover, due to the changes in the electrodes during charging and discharging processes, mechanical instability may occur [9, 19]. In thick electrodes, the accumulation of stress will lead to electrode cracking and peeling [9].

By constructing a nano-conductive network, the electronic conductivity can be enhanced. Traditional conductive agents, such as carbon black, require point-to-point contact for conductivity, resulting in high resistance [19]. However, using carbon nanotubes can form a continuous and highly conductive network, significantly improving the efficiency of electron transmission [19]. This can solve the problem of electronic conductivity [19]. The issue of ion transmission can be addressed by combining nano materials and active materials to form a directional, layered pore structure, thereby optimizing the ion transmission channels and making the ion transmission smoother and uniform [19]. In terms of mechanical integrity, carbon nanotubes can also form a three-dimensional porous mechanical framework, which is beneficial for preventing the migration of active material particles, alleviating volume changes, and maintaining the stability of the conductive network [19]. A battery containing 1 wt% of carbon nanotubes maintained an energy density of 81.7% after undergoing 400 charging and discharging cycles [20].

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2.3. Results & discussion

Table 1. The influence of nanomaterials on the energy density of batteries

Nano Materials/Structures	Lifecycle	Majar Challenge	Energy density
TiO2 cathode nano-coating	500	Side effects	The original 72.2%
Nanosilicon spheres	250	Volume expansion of silicon	The original 65%
Silicon Nanotubes	/	Volume expansion of silicon	1277.2 Wh/kg
1 wt% of single-walled carbon nanotubes	400	Ion transport limitation	The original 81.7%(about 402.781)

To mitigate the intrinsic limitations of high-energy-density electrodes, nanotechnology tunes composition, interfaces, and architecture at the nanoscale. Comparative electrochemical datasets consistently show substantial performance gains.

High-nickel layered cathodes are limited by interfacial parasitic reactions and Ni/Li cation disorder, both of which curtail long-cycle stability. Coating cathode particles with stable inorganic nanomaterials is highly effective. As Table 1 shows, a nano-TiO_2 coating acts as an effective physical barrier, keeping the cathode separated from the corrosive electrolyte. Capacity retention of 72.2% after 500 cycles is achieved. In contrast, uncoated controls lose much capacity - often less than 60% after 200 cycles. This marked difference highlights how key nanoscale surface passivation is. The nano-coating is thin enough not to hinder lithium-ion diffusion, yet robust enough to stop side reactions and oxygen release, stabilizing the cathode's structure for long-cycle high capacity.

Similarly, silicon anodes'over 300% volume change drives mechanical failure without architectural control. Nano-structure design (not composition changes) addresses this directly. Representative literature shows that optimized silicon nanostructures perform well in cycling. For example, connected silicon hollow nano-Si spheres still have the original 65% capacity after 250 cycles. The reason is that the hollow inside offers expansion space, and the thin shell shortens lithium-ion diffusion paths - mitigating mechanical damage at the root. Also, silicon nanotube electrodes have 1277.2 Wh/kg reversible capacity, as they expand radially freely without destructive stress. These results prove nano-structures that handle mechanical stress boost next-gen anodes' energy density.

In short, nanotechnology addresses EV battery energy-density bottlenecks via two complementary routes: (1) nano-modifying/designing active materials (e.g., high-Ni cathodes, Si anodes) to boost intrinsic capacity and stability - solving the "storing more energy" problem; and (2) engineering precise nano-functional interphases and architectures (e.g., artificial SEI, thick-electrode nano-networks) to ensure efficient ion/electron transport and interface stability - solving the "delivering energy reliably at practical rates" problem. Though large-scale nanomaterial production, cost control, and manufacturability remain challenging, the evidence surveyed here underscores nanotechnology as a core enabling technology for high-energy-density EV cells.

3. Conclusion

The primary challenge for the next-generation electric vehicle batteries is raising energy density. This review shows how nanotechnology can precisely adjust chemical composition, interfaces and structure, forming a practical tool for breaking through the energy density limitations.

The key conclusions are as follows: Firstly, chemistry-centred nano-engineering directly enhances the capacity and stability of active materials. For instance, nanoscale TiO_2 coatings on

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high-Ni cathodes reduce interface damage and cation disorder; after 500 cycles, 72.2% capacity retention is observed. Designing hollow nano-spheres and nano-tubes for the silicon negative electrode can cope with its over 300% volume expansion, and after 700 cycles, it still has a high capacity of 568 Wh/kg. Secondly, nanotechnology engineering around interfaces and structures can ensure efficient and continuous energy release. For example, designing a nano-composite artificial SEI with ionic conductivity and electron blocking functions, and constructing a thick electrode with a nano-conductive network using carbon nanotubes, respectively, solves the problems of unstable interfaces and slow mass transfer.

These strategies can effectively alleviate the structural problems of high-nickel batteries, the volume expansion issues of silicon-based batteries, artificial SEI, and the problems of thick electrodes. However, there are still some issues that need to be addressed, such as the large-scale production of nanomaterials, cost control, and long-term environmental impacts. Only in this way can nanotechnology contribute to sustainable electric transportation.

References

[1] Pierri, E., Cirillo, V., Vietor, T., & Sorrentino, M. (2021). Adopting a conversion design approach to maximize the energy density of battery packs in electric vehicles. Energies, 14(7), 1939. https: //doi.org/10.3390/en14071939

[2] Tesla, Inc. (2024, May 17). 4680 battery cell specifications. https: //www.tesla.com/...(Retrieved 17 August 2025). 4. Liu, Y., Liu, S., Li, G., & Gao, X. (2020). Strategy of enhancing the volumetric energy density for Lithium–Sulfur batteries. Advanced Materials, 33(8). https: //doi.org/10.1002/adma.202003955

[3] Abraham, K. M. (2015). Prospects and Limits of energy storage in batteries. The Journal of Physical Chemistry Letters, 6(5), 830–844. https: //doi.org/10.1021/jz5026273

[4] Vermeer, W., Chandra Mouli, G. R., & Pavol Bauer. (2022). A comprehensive review on the characteristics and modeling of Lithium-Ion battery aging. In IEEE TRANSACTIONS ON TRANSPORTATION ELECTRIFICATION (Vol. 8, Issue 2, pp. 2205–2206).

[5] Sullivan, J. L., Gaines, L., Center for Transportation Research, & Energy Systems Division, Argonne National Laboratory. (2010). A review of Battery Life-Cycle Analysis: State of Knowledge and Critical Needs. In Energy Systems Division. https: //publications.anl.gov/anlpubs/2010/11/68455.pdf

[6] Waldmann, T., Wilka, M., Kasper, M., Fleischhammer, M., & Wohlfahrt-Mehrens, M. (2014). Temperature dependent ageing mechanisms in Lithium-ion batteries – A Post-Mortem study. Journal of Power Sources, 262, 129–135. https: //doi.org/10.1016/j.jpowsour.2014.03.112

[7] Zhang, C., Wang, F., Han, J., Bai, S., Tan, J., Liu, J., & Li, F. (2021). Challenges and recent progress on Silicon-Based anode materials for Next-Generation Lithium-Ion batteries. Small Structures, 2(6). https: //doi.org/10.1002/sstr.202100009

[8] Park, K., Park, J., Seong, W. M., Yoon, K., Hwang, T., Ko, K., Han, J., Jaedong, Y., & Kang, K. (2020). Understanding capacity fading mechanism of thick electrodes for lithium-ion rechargeable batteries. Journal of Power Sources, 468, 228369. https: //doi.org/10.1016/j.jpowsour.2020.228369

[9] Zheng, J., Xing, G., Jin, L., Lu, Y., Qin, N., Gao, S., & Jim P. Zheng. (2023). Strategies and Challenge of Thick electrodes for Energy Storage: A review. In Palani Balaya (Ed.), Batteries (p. 151). https: //doi.org/10.3390/batteries9030151

[10] Kim, Y., Seong, W. M., & Manthiram, A. (2020b). Cobalt-free, high-nickel layered oxide cathodes for lithium-ion batteries: Progress, challenges, and perspectives. Energy Storage Materials, 34, 250–259. https: //doi.org/10.1016/j.ensm.2020.09.020

[11] Jeevanantham, B., Shobana, M., Su, W., & Hwang, B. J. (2024). Surface engineering of TiSiO4 nano-coating for high-voltage nickel-rich ternary cathodes: An approach to improve cyclic performance. Journal of Energy Storage, 100, 113546. https: //doi.org/10.1016/j.est.2024.113546

[12] Delmas, C., Braconnier, J., Fouassier, C., & Hagenmuller, P. (1981). Electrochemical intercalation of sodium in NaxCoO2 bronzes. Solid State Ionics, 3–4, 165–169. https: //doi.org/10.1016/0167-2738(81)90076-x

[13] Kang, K., & Ceder, G. (2006). Factors that affect Li mobility in layered lithium transition metal oxides. Physical Review B, 74(9). https: //doi.org/10.1103/physrevb.74.094105

[14] Zheng, J., Ye, Y., Liu, T., Xiao, Y., Wang, C., Wang, F., & Pan, F. (2019). NI/LI Disordering in Layered Transition Metal Oxide: Electrochemical impact, origin, and control. Accounts of Chemical Research, 52(8), 2201–2209.

DOI: 10.54254/2755-2721/2025.GL27679

https: //doi.org/10.1021/acs.accounts.9b00033
[15] Jaumann, T., Gerwig, M., Balach, J., Oswald, S., Brendler, E., Hauser, R., Kieback, B., Eckert, J., Giebeler, L., & Kroke, E. (2017c). Dichlorosilane-derived nano-silicon inside hollow carbon spheres as a high-performance anode for Li-ion batteries. Journal of Materials Chemistry A, 5(19), 9262–9271. https: //doi.org/10.1039/c7ta00188f
[16] Wang, W., & Kumta, P. N. (2010). Nanostructured hybrid Silicon/Carbon nanotube heterostructures: reversible High-Capacity Lithium-Ion anodes. ACS Nano, 4(4), 2233–2241. https: //doi.org/10.1021/nn901632g
[17] Moorthy, M., Thangavel, R., An, S., Anilkumar, A., Han, D., & Lee, Y. S. (2025). Recent trends in artificial SEI layers for controlling dendrite formation and enhancing cycle life: toward stable and durable sodium metal batteries. Small. https: //doi.org/10.1002/smll.202502974
[18] Meda, U. S., Lal, L., M, S., & Garg, P. (2021). Solid Electrolyte Interphase (SEI), a boon or a bane for lithium batteries: A review on the recent advances. Journal of Energy Storage, 47, 103564. https: //doi.org/10.1016/j.est.2021.103564
[19] Pokhriyal, A., González-Gil, R. M., Bengoa, L. N., & Gómez-Romero, P. (2023b). Nanostructured Thick Electrode Strategies toward Enhanced Electrode–Electrolyte Interfaces. Materials, 16(9), 3439. https: //doi.org/10.3390/ma16093439
[20] Wang, H., Chao, Y., Li, J., Qi, Q., Lu, J., Yan, P., Nie, Y., Wang, L., Chen, J., & Cui, X. (2024). What is the real origin of Single-Walled carbon nanotubes for the performance enhancement of SI-Based anodes? Journal of the American Chemical Society, 146(25), 17041–17053. https: //doi.org/10.1021/jacs.4c01677