Proceedings of CONF-MCEE 2026 Symposium: Advances in Sustainable Aviation and Aerospace Vehicle Automation
DOI: 10.54254/2755-2721/2026.KA27924

Silicon Anodes for Lithium-Ion Batteries: Advancements and Pathways to Industrialization

Yixuan Wu

Department of Materials Science, Nanjing University of Aeronautics and Astronautics, Nanjing, China
wyxnzb@nuaa.edu.cn

Abstract. Silicon-based anodes offer significant potential for advancing lithium-ion battery technology due to their high theoretical capacity and abundant resources. However, challenges such as volume expansion and poor conductivity have hindered their commercial scalability. This review focuses on the future industrialization of silicon anodes, with an emphasis on solid-state battery (SSB) integration. Strategies for improving performance, such as structure regulation, and pre-lithiation techniques, are discussed in the context of enhancing the practical application of silicon anodes. The potential of solid-state systems to improve safety, energy density, and cycle life while simplifying battery design is explored. This review provides a forward-looking perspective on the commercialization of silicon anodes, highlighting their role in the next generation of high-performance, safe, and scalable energy storage solutions.

Keywords: Silicon anodes, structure regulation, pre-lithiation strategies, in LIB or SSB

1. Introduction

Silicon has abundant reserves (26.3%) and is widely available in nature, typically found in the form of silicates or silica. It can be produced on a large scale through reactions such as carbon reduction, making it industrially scalable and commercially available. Additionally, silicon itself is non-toxic and does not pollute the environment. If combined with mature technologies from the photovoltaic and semiconductor industries, it could further reduce costs on a larger scale [1,2].

From the perspective of energy storage mechanisms, Silicon, as an alloy mechanism anode material(appropriate lithium plating potential～0.4 V vs. Li^+/Li), easily forms Li_xM alloy phases with lithium. The greatest advantage of such materials is their high theoretical specific capacity (3579 mA h g^{-1} for $Li_{15}Si_4$, about ten times closer to commercial graphite).Commercial lithium-ion batteries typically use graphite as the anode, which has a theoretical capacity of 372 mA h g^{-1} (LiC_6). Silicon has a high specific capacity similar to that of lithium metal while relatively low lithiation voltage(which can avoid lithium deposition at the risks of puncturing the separator and causing short circuits [3], making it an attractive candidate for use in lithium-ion batteries. However, despite its promising potential, the practical implementation of silicon anodes is hindered by several challenges, one of the most significant being the issue of volume expansion during the lithiation process. When silicon alloys with lithium, it undergoes a substantial volume increase—

© 2026 The Authors. This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (https://creativecommons.org/licenses/by/4.0/).

DOI: 10.54254/2755-2721/2026.KA27924

approximately 280%—which causes mechanical stress and structural degradation of the anode material. This expansion leads to particle crack and fragmentation, which subsequently damages the electrode structure, ultimately causing delamination between the coating and the current collector [4,5]. It also disrupts the structural integrity of the SEI layer. Moreover, crushed silicon particles and overgrown SEI layers further crush and damage the electrode structure, exacerbating issues of low electronic conductivity and slow ion mobility.

Also, as a semiconductor material, the inherent ion mobility (10^{-14}~10^{-13} cm^2 s^{-1}) and electronic conductivity (10^{-5}~10^{-3} S cm^{-1}) of Si are much lower than those of graphite materials, resulting in unsatisfactory rate performance of Si-based electrodes [6]. Due to the slow migration of ions, during charging and discharging, a significant concentration gradient forms within the electrodes, causing the working voltage to deviate from the equilibrium potential (increased polarization), which reduces the effective working voltage platform of the battery, generates more heat and decreases efficiency.

Despite these challenges, the potential of silicon anodes in improving the performance of lithium-ion batteries remains immense. This review focuses on the practical strategies that have been developed to enhance the performance of silicon anodes, including structure regulation and pre-lithiation techniques. Additionally, the integration of silicon anodes with solid-state battery technologies presents a promising path forward, offering improved safety, energy density, and cycle life. The following sections will explore these strategies in detail and discuss their role in overcoming the current barriers to silicon anode commercialization, with an emphasis on their industrialization prospects.

2. Structure regulation of silicon anode

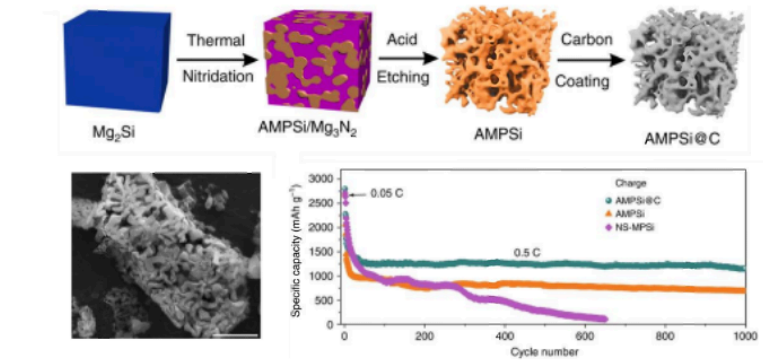
Silicon anode materials offer exceptional theoretical capacity, but their practical application is hindered by challenges such as volume expansion and poor conductivity. To address these issues, structural design has become a crucial strategy. Reducing bulk silicon to the nanoscale dimensions (less than the critical size 150 nm) shows resistance to stress caused by repeated volume changes, which can prevent crack propagation because the strain energy stored by electrochemical reactions is reduced [7,8]. However, compared to nanosacle materials prepared by chemical vapor deposition using SiH_4 or through a series of complex methods, micrometer silicon(SiMP) is usually manufactured through a simple mechanical grinding process, demonstrating more competitive cost-effectiveness [9]. Meanwhile, the larger particle size greatly reduces the specific surface area, decreasing the irreversible lithium-ion consumption caused by electrolyte decomposition. Importantly, SiMP typically have higher tap density, allowing for higher mass loading at the same electrode thickness, which helps to improve the areal capacity and volumetric energy density. Thus, applying structure relugations to SiMP anodes has significant commercial value.

An et al. proposed a scalable method for synthesizing ant-nest-like porous silicon by thermally nitriding magnesium-silicon alloys [10]. This material features three-dimensional interconnected silicon nanoligaments and a bicontinuous nanoporous network, which effectively prevents pulverization and accommodates volume expansion, ensuring excellent cycling stability(Figure 1 (a)). Specifically, the carbon-coated AMPSi@C anode material exhibits a high capacity of 1271 mA h g^{-1} at a high current rate and retains 90% of its capacity after 1000 cycles. Moreover, it demonstrates minimal electrode swelling of only 17.8%, highlighting its superior performance in terms of high energy density and long cycle life.

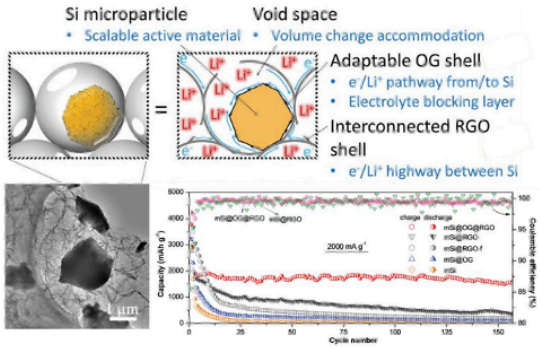
Zhang et al. [11] proposed a scallop-inspired shell engineering strategy to construct high volumetric capacity, binder-free silicon-based anodes as shown in Figure 1 (b). The design features a

DOI: 10.54254/2755-2721/2026.KA27924

bilayer graphene shell on silicon microparticles: an inner overlapping graphene (OG) shell stabilizing the interface and promoting electron/ion transport, and an outer reduced graphene oxide (RGO) hollow shell providing a conductive network and buffering volume expansion. The mSi@OG@RGO self-supporting electrode exhibits excellent Coulombic efficiency, rate performance, and cycling stability (>150 cycles, 1750 mA h g^{-1} capacity retention). After simple pressing, it achieves a volumetric capacity of 1697 mA h cm^{-3}, surpassing commercial graphite anodes. This approach offers new insights into designing electrodes with high volumetric expansion.



(a) The preparation of AMPSi@C and its SEM image (scale bar = 2 μm), demonstrating excellent long-cycle performance at 0.5 C after activation (1 C = 4.2 A g^{-1}) in the half-cell [10]



(b) The structure and theTEM image and the cycling performance curves of mSi@OG@RGO [11]

Figure 1. Two biomimetic structural design strategies in boosting volumetric capacity and cycling stability

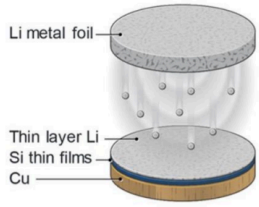
3. Pre-lithiation strategies for silicon anodes

Pre-lithiation has become a critical technique in overcoming the challenges associated with silicon anodes, particularly in terms of the significant capacity loss during the first few cycles. Silicon anodes undergo a substantial volume expansion when they alloy with lithium, leading to mechanical degradation and a loss of active material. Pre-lithiation addresses this issue by introducing lithium into the silicon structure prior to battery cycling, effectively reducing the initial capacity loss and stabilizing the structure during the first charge-discharge cycles. This process enhances the initial cycle efficiency and prolongs the overall life cycle of the battery. By improving the performance of silicon anodes from the outset, pre-lithiation plays a key role in making silicon-based anodes more commercially viable, facilitating their adoption in large-scale applications for next-generation lithium-ion batteries.

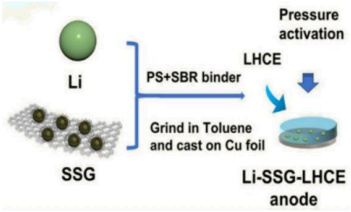
DOI: 10.54254/2755-2721/2026.KA27924

Adhitama et al. [12] developed a pre-lithiation method using thermal evaporation of lithium (Li) metal onto Si thin films as shown in Figure 2 (a). This technique ensures uniform lithium distribution and precise control over the degree of pre-lithiation. The approach improves cycle stability and minimizes lithium loss due to SEI formation, offering a reproducible and scalable solution for enhancing long-term cycling stability of Si-based anodes.

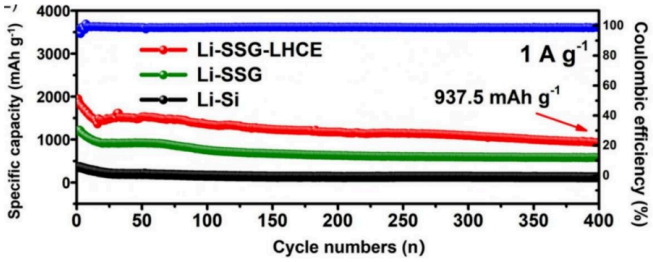
Zhang et al. [13] proposed pre-lithiation using a localized high-concentration electrolyte (LHCE) for Si-carbon composite anodes (Figure 2 (b)). This method ensures uniform Li deposition and stabilizes the SEI, improving initial Coulombic efficiency (ICE). The Si-carbon anodes achieved a high reversible capacity of 937.5 mA h g^{-1} after 400 cycles at 1 A g^{-1} (Figure 2 (c)), demonstrating superior performance and potential for large-scale LIB applications.



(a) Thin later Li deposition using Li thermal evaporation [12]



(b) Prelithiation process for SSG anode to achieve the Li-SSG-LHCE anode [13]



(c) Long-term cycling performance of Li-SSG-LHCE anode at a current density of 1 A g^{-1} [13]

Figure 2. Pre-lithiation strategies used in improving the homogeneity and stability of SEI and long-term cycle life

4. Silicon anodes in solid-state battery systems

Generally, solid-state electrolyte materials are classified into four major categories: sulfide polymers, oxide polymers, halide polymers, and polymer polymers. Solid-state electrolytes based on sulfides have garnered significant attention due to their extremely high ionic conductivity (the Cl-rich argyrodite $Li_{5.5}PS_{4.5}Cl_{1.5}$'s sintered ionic conductivity can achieve 12.0 mS /cm [14]). The immense pressure (50 MPa) during battery assembly can create a well-contacted initial solid-solid interface, while to some extent suppressing the volumetric expansion of silicon [15]. Therefore, pairing sulfide solid-state electrolytes with silicon anodes can maximize the capacity advantages of silicon anodes. However, the following urgent issues need to be addressed in the transition to sulfide all-solid-state batteries: 1) Constructing a complete ion/electron conductive network at the electrode scale; 2) Pre-lithiation methods in solid-state systems; 3) Stability under low pressure/no pressure.

Silicon itself has poor electrical conductivity and significant volume changes, which can easily lead to electrode structural damage. By constructing a continuous conductive network, not only can the electrical conductivity be improved, but stress can also be alleviated, maintaining the integrity of the electrode structure. For example, Qiao et al. [16] prepared self-supporting silicon-graphite integrated electrodes (SGCI) through pressure carbonization of pitch as shown in Figure 3 (a),

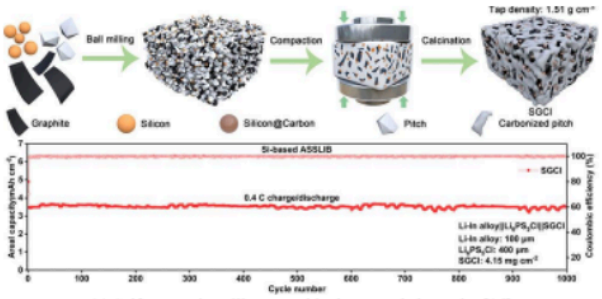
DOI: 10.54254/2755-2721/2026.KA27924

achieving a high tap density of 1.51 g cm^{-3} and a very low longitudinal expansion rate (<20%). In liquid and all-solid-state batteries, they exhibited a capacity retention of 77.6% (after 500 cycles) and 98.5% (after 1000 cycles), respectively, and supported a high areal capacity of 12.6 mA h cm^{-2}. On the other hand, Li et al. [17] proposed using a lithium-indium alloy as a mixed conductive medium(Figure 3 (b)), constructing a three-dimensional ion-electron dual-pathway network through molten indium infiltration, significantly enhancing the electrode's electrical conductivity and lithium-ion diffusion ability. This allowed ASSBs to maintain a capacity retention of 98.5% after 2000 cycles, with an areal capacity as high as 13.4 mA h cm^{-2}. These two studies jointly indicate that constructing a continuous and stable conductive network is a key strategy for achieving.

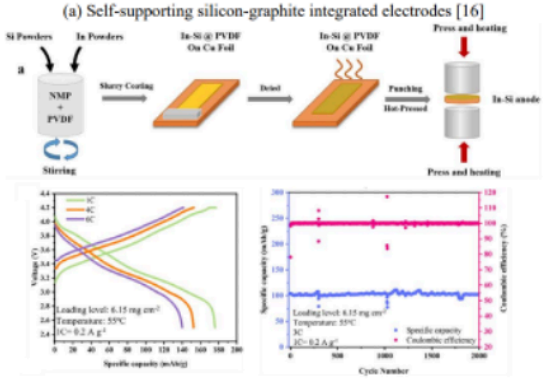
Pre-lithiation is a key strategy to address the low initial coulombic efficiency (ICE) and poor conductivity issues of silicon-based all-solid-state batteries (ASSBs). Ham et al. [18] successfully prepared Li_xSi (x=0.25, 1, 2) alloy anodes by mixing stabilized lithium metal powder (SLMP) with micron-sized silicon (mSi) and applying pressure between 200-400 MPa using a simple and efficient pressure-induced pre-lithiation method as shown in Figure 3 (c). This strategy significantly improved the electronic conductivity of the silicon anode, from 10^{-4} S/cm to 10 S/cm, and increased the ICE of the Li_2Si‖LCO full cell to 95.7%, far higher than the 78.3% of the non-pre-lithiated system. The pre-lithiation effect is highly dependent on the type of full-cell limitation: it is only effective in LCO-Si. Additionally, pre-lithiation effectively compensates for the irreversible capacity loss due to interfacial side reactions and lithium plating/stripping during the first cycle, allowing the Li_1Si‖LCO battery to maintain 73.8% capacity after 1000 cycles at 5 mA cm^{-2}, a 15% improvement over the non-pre-lithiated system. Combining this pre-lithiation strategy with dry electrode processing further supports the design of high areal capacity of 10 mA h cm^{-2}, demonstrating its broad application potential in next-generation high-energy-density all-solid-state batteries.

The practical application of silicon-based solid-state batteries has long been limited by the dependence on high external stacking pressure [19-20], typically requiring tens to hundreds of megapascals (MPa) of pressure to maintain the interface stability between the electrodes and the solid-state electrolyte (SSE) and to suppress the volume expansion of the silicon anode [21]. This requirement not only increases system complexity and cost but also severely hinders its scaling and commercialization process. Recently, Zhang et al. [22] proposed an innovative double-layered anode design: $Li_{21}Si_5$/Si–$Li_{21}Si_5$, successfully achieving efficient operation of silicon-based all-solid-state batteries without the need for external high pressure. This design constructs a top layer with mixed ion/electron conductivity using $Li_{21}Si_5$ and a bottom layer rich in a three-dimensional continuous conductive network using Si–$Li_{21}Si_5$ through cold pressing and sintering technology(Figure 3 (d)). This structure not only forms a uniform electric field at the anode/SSE interface, significantly enhancing lithium ion flux (increasing by about two times), but also effectively disperses the expansion stress of silicon particles during cycling, thereby avoiding interface damage and the formation of lithium dendrites. The battery achieved a critical current density of 10 mA cm^{-2} and an areal capacity of 10 mA h cm^{-2} at 45°C, while demonstrating an initial Coulombic efficiency as high as (97 ± 0.7)% and a low expansion rate of only 14.5% after 1000 cycles. These performance metrics are groundbreaking under no external pressure conditions, indicating significant advantages in improving interfacial stability and electrochemical performance, providing a crucial technical path for the development of next-generation solid-state batteries that are low-cost, high-safety, and high-energy-density.

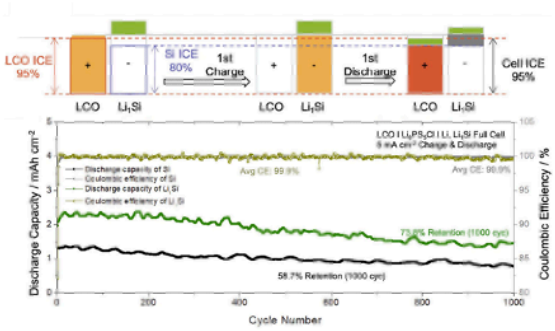
DOI: 10.54254/2755-2721/2026.KA27924



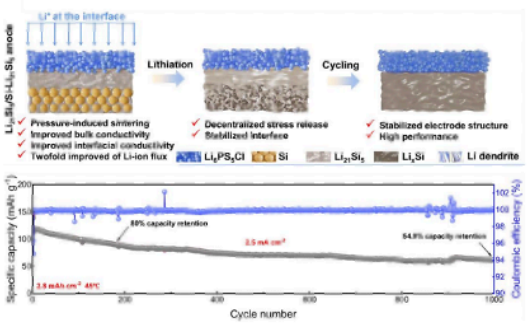
(a) Self-supporting silicon-graphite integrated electrodes [16]



(b) 3D ion-electron dual-pathway network through molten indium infiltration [17]



(c) Pressure-induced pre-lithiation method [18]



(d) Double-layered anode design [22]

Figure 3. Representative works on silicon anodes in solid-state battery systems

5. Conclusion and outlook

Silicon-based anodes hold significant promise for the next generation of lithium-ion batteries, offering substantial improvements in capacity and energy density compared to traditional graphite anodes. However, challenges such as the dramatic volume expansion during lithiation and the resulting mechanical failure must be overcome to enable their large-scale commercial application.

DOI: 10.54254/2755-2721/2026.KA27924

Structural design and pre-lithiation techniques have been identified as critical strategies in mitigating these issues, ensuring better cycle stability and improving initial efficiency.

Looking ahead, the integration of silicon anodes with all-solid-state batteries (SSBs) offers an exciting avenue for the future of energy storage. The potential of solid-state electrolytes to enhance safety, volumetric efficiency, and overall performance provides an ideal platform for fully realizing the benefits of silicon anodes. As research continues to progress, advancements in pre-lithiation, structural optimization, and solid-state electrolyte development will likely address many of the current limitations, paving the way for more robust, high-energy-density batteries.

The commercialization of silicon-based solid-state batteries will rely heavily on scaling up manufacturing processes, improving cost-effectiveness, and ensuring long-term stability. With ongoing innovations in materials and technology, silicon anodes, paired with solid-state systems, are poised to play a pivotal role in shaping the future of energy storage, offering more efficient, safe, and sustainable solutions for a wide range of applications.

References

[1] Yang, Y., Dong, H., Yu, K., Song, Q., Ning, Z., & Xie, H. (2025). Electrochemical etching of photovoltaic micron-silicon scrap in molten KCl-LiCl for high-performance lithium-ion battery anodes. Chinese Chemical Letters, 38(2), 111492. https: //doi.org/10.1016/j.cclet.2025.01.001

[2] Zhang, Y., Ma, H., Yu, C., Feng, X. (2023). Si nanoplates prepared by ball milling photovoltaic silicon sawdust waste as lithium-ion batteries anode material. Materials Letters, 331, 133469. https: //doi.org/10.1016/j.matlet.2023.133469

[3] Huang, W.-Z., Zhao, C.-Z., Wu, P., Yuan, H., Feng, W.-E., Liu, Z.-Y., ... Zhang, Q. (2022). Anode-free solid-state lithium batteries: A review. Advanced Energy Materials, 12, 2201044. https: //doi.org/10.1002/aenm.202201044

[4] Feng, K., Li, M., Liu, W., Kashkooli, A. G., Xiao, X., Cai, M., ... (2018). In situ atomic-scale imaging of electrochemical lithiation in silicon. Small, 14, 1702737. https: //doi.org/10.1002/smll.201702737

[5] Zhang, Y., Wu, B., Mu, G., Ma, C., Mu, D., & Wu, F. (2022). Recent progress and perspectives on silicon anode: Synthesis and prelithiation for LIBs energy storage. Journal of Energy Chemistry, 64, 615–650. https: //doi.org/10.1016/j.jech.2022.05.034

[6] Thackeray, M. M., Wolverton, C., & Isaacs, E. D. (2012). Electrical energy storage for transportation—approaching the limits of, and going beyond, lithium-ion batteries. Energy & Environmental Science, 5(7), 7854–7863. https: //doi.org/10.1039/C2EE00085J

[7] Zhao, Z., Chen, F., Han, J., ... (2023). Revival of microparticular silicon for superior lithium storage. Advanced Energy Materials, 13(24), 2300367. https: //doi.org/10.1002/aenm.202300367

[8] Zhu, G., Chao, D., Xu, W., ... (2021). Microscale silicon-based anodes: Fundamental understanding and industrial prospects for practical high-energy lithium-ion batteries. ACS Nano, 15(10), 15567–15593. https: //doi.org/10.1021/acsnano.1c03456

[9] Xiao, Z., Yu, C., Lin, X., Chen, X., Zhang, C., Jiang, H., & Zhang, R. (2020). TiO_2 as a multifunction coating layer to enhance the electrochemical performance of SiO_x@TiO_2@C composite as anode material. Nano Energy, 77, 105082. https: //doi.org/10.1016/j.nanoen.2020.105082

[10] An, W., Gao, B., Mei, S., ... (2019). Scalable synthesis of ant-nest-like bulk porous silicon for high-performance lithium-ion battery anodes. Nature Communications, 10(1), 1447. https: //doi.org/10.1038/s41467-019-09144-y

[11] Zhang, X., Guo, R., Li, X., & Zhi, L. (2018). Scallop-inspired shell engineering of microparticles for stable and high volumetric capacity battery anodes. Small, 14, 1800752. https: //doi.org/10.1002/smll.201800752

[12] Adhitama, E., ... (2022). Pre-lithiation of silicon anodes by thermal evaporation of lithium for boosting the energy density of lithium-ion cells. Advanced Functional Materials, 32, 2201455. https: //doi.org/10.1002/adfm.202201455

[13] Zhang, Y., Wu, B., … (2024). Facilitating prelithiation of silicon carbon anode by localized high-concentration electrolyte for high-rate and long-cycle lithium storage. Carbon Energy. https: //doi.org/10.1002/cey2.480

[14] Adeli, P., Bazak, J. D., Park, K. H., ... (2019). Boosting solid-state diffusivity and conductivity in lithium superionic argyrodites by halide substitution. Angewandte Chemie International Edition, 58(38), 8681–8686. https: //doi.org/10.1002/anie.201904786

[15] Wu, Z., Li, X., Zheng, C., ... (2023). Interfaces in sulfide solid electrolyte-based all-solid-state lithium batteries: Characterization, mechanism and strategy. Electrochemical Energy Reviews, 6(10), 10. https:

DOI: 10.54254/2755-2721/2026.KA27924

//doi.org/10.1007/s42925-023-00123-w
[16] Qiao, R., Shen, X., Mao, C., ... (2024). High-strength silicon anodes with high tap density via compression carbonization for liquid and all-solid-state lithium-ion batteries. Nano Letters, 24(49), 15629–15637. https: //doi.org/10.1021/acs.nanolett.4c02567
[17] Li, R., Zeng, J., Wang, P., ... (2025). A high-performance silicon-based anode enabled by hybrid pathways for all-solid-state batteries. Advanced Energy Materials, e02913. https: //doi.org/10.1002/aenm.202502913
[18] Ham, S. Y., Sebti, E., Cronk, A., ... (2024). Overcoming low initial coulombic efficiencies of Si anodes through prelithiation in all-solid-state batteries. Nature Communications, 15(1), 2991. https: //doi.org/10.1038/s41467-024-46789-w
[19] Janek, J., & Zeier, W. G. (2023). Challenges in speeding up solid-state battery development. Nature Energy, 8(3), 230–240. https: //doi.org/10.1038/s41560-023-01234-x.
[20] Ren, D., ... (2023). Challenges and opportunities of practical sulfide-based all-solid-state batteries. eTransportation, 18, 100272. https: //doi.org/10.1016/j.etran.2023.100272
[21] Luo, L., ... (2023). Tuning the electron transport behavior at Li/LATP interface for enhanced cyclability of solid-state Li batteries. Nano Research, 16(5), 1634–1641. https: //doi.org/10.1007/s12274-023-5567-y
[22] Zhang, Z., Zhang, X., Liu, Y., ... (2025). Silicon-based all-solid-state batteries operating free from external pressure. Nature Communications, 16(1), 1013. https: //doi.org/10.1038/s41467-025-56789-z