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Preview

Bio-morphogenesis relieves pressure in all-solid-state batteries

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The practical application of all-solid-state batteries is hindered by the high pressure required for cell operation. In a recent issue of *Science*, Yoon et al. developed a Li-Na composite anode operable at low pressures below 1 MPa, utilizing bio-inspired morphogenesis of Na at the anode-electrolyte interface.

All-solid-state lithium metal batteries (ASSLMBs) hold promise as a next-generation energy storage solution, as they simultaneously offer high energy density, long cycle life, and significantly improved thermal stability.[1,2] Despite these advantages, a major hurdle in commercializing ASSLMBs comes from issues with interfacial instability between the solid electrolyte and the electrode, such as void formation and contact loss.[3] Such a challenge stems from the fact that solid electrolytes cannot flow as readily as their liquid counterparts, making the conformal and intimate interfaces difficult to maintain. As a result, high stack pressures (e.g., $\gg$1 MPa) are typically required to suppress void formation and preserve intimate interfacial contacts among different components in ASSLMBs.[4–6] Unfortunately, such mechanical constraints are often impractical for commercial battery systems.

In a recent issue of *Science*, Yoon et al. presented a novel, bio-inspired strategy to improve interfacial stability in lithium (Li) metal anodes under low pressure. Drawing inspiration from biological morphogenesis—where cells self-organize through chemo-mechanical feedback—they introduce metallic sodium (Na), a deformable and electrochemically inactive secondary phase, into the Li matrix (Figures 1A and 1B).[7] To achieve this, they incorporate 2.5–20 mol % Na into Li using accumulative roll bonding, a process involving repeated mixing, folding, and cold rolling of Li and Na to form a uniform composite structure. Na is mechanically softer and electrochemically inactive at the redox potential of Li^+/Li, allowing it to migrate and deform toward the Li-solid electrolyte interface during Li stripping. This spontaneous accumulation suppresses void formation, maintains electrical contact, and supports uniform Li-ion transport without obstructing Li plating and stripping.

Galvanostatic voltage profiles during Li stripping demonstrate that the Li-Na composite electrode outperforms pure Li anode at low stack pressures (0–3.2 MPa, Figures 1C and 1D). At 0.8 MPa, the Li-Na composite anode with 5% Na achieves 16 mAh cm^{-2} of stripping, while the pure Li anode exhibits <3 mAh cm^{-2} of stripping under the same conditions. Remarkably, a 20% Na electrode can retain over 5 mAh cm^{-2} even without an external pressure, highlighting the advantageous role of mixed Na phases in sustaining contact. Operando X-ray computed tomography (XCT) and cryo-focused ion beam (FIB)-scanning electron microscopy (SEM) imaging further confirm that Na domains migrate to the solid-state electrolyte (SSE) interface after stripping (Figures 1E and 1F), enabling morphogenic interfacial adaption. Simulations based on XCT data reveal that interfacial Na coverage increases progressively as Li is removed—a response that becomes more pronounced after initial cycling due to altered Na microstructures.

A mesoscale model further reveals that Na domains at the Li-SSE interface homogenize stress distribution and suppress void growth by undergoing plastic deformation and creep, owing to the 54% lower hardness of Na compared with Li (8.9 MPa vs. 16.5 MPa). Under a stack pressure of 1 MPa and a current density of 0.5 mA cm^{-2}, simulations show that Na domains maintained higher interfacial contact and substantially reduced current focusing, resulting in a more uniform potential distribution. Notably, voids at the anode-electrolyte interface become smaller with Li-Na anode, opposite to voids in pure Li anode, which relieves the stripping delamination (Figure 1G). The proposed addition of Na incurs only a 1%–2% reduction in the cell-level specific energy, making the trade-off highly favorable.

The Li-Na composite anode shows stable cycling in long-term galvanostatic cycling tests of symmetric cells (Figure 1H). At a current density of 0.75 mA cm^{-2} and a stack pressure of 2.5 MPa, the 5% Na electrode demonstrates stable cycling exceeding 100 cycles. Similarly, the 10% Na electrode, operated at a lower current density of 0.5 mA cm^{-2} and a reduced stack pressure of 1.6 MPa, maintains stable cycling for over 50 cycles. By contrast, a pure Li electrode subjected to identical conditions exhibits rapid voltage polarization during the stripping phase before subsequently short-circuiting during plating. In full-cell tests with sulfur cathodes, the anode containing 5% Na sustains a capacity retention of 75% over 100 cycles at 2.5 MPa and a cathode loading of 5.1 mg_{sulfur} cm^{-2}. Similarly, the 10% Na anode achieves a capacity retention of 63% over 69 cycles at only 0.8 MPa and 0.5 mA cm^{-2}. By contrast, cells with pure Li anodes fail within a few cycles under similar conditions. The proposed Li-Na composite anode demonstrates a particularly noteworthy ability to enable low-pressure cell operation (<1 MPa). This capability arises from the morphogenetic process in which the redistribution

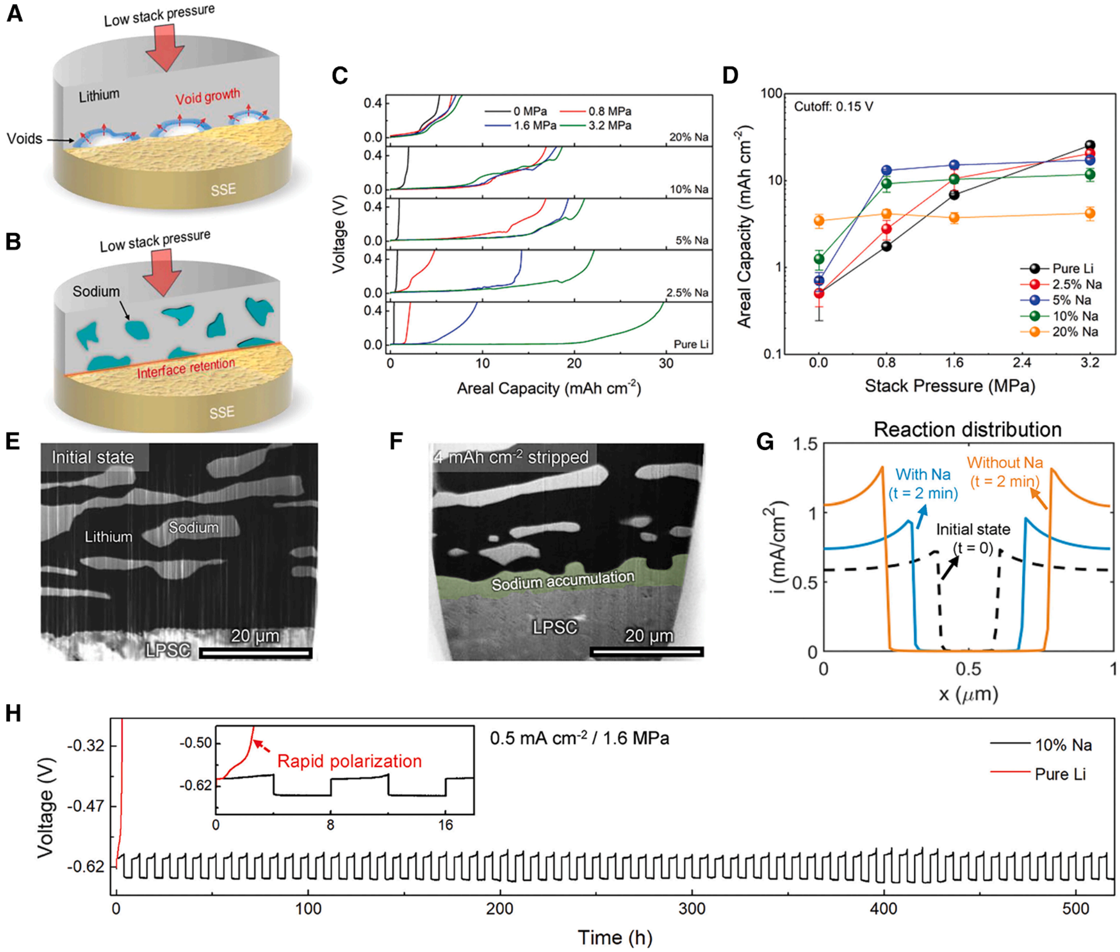

Figure 1. Interfacial pore-filling behavior of Li-Na composite anode through the bio-morphogenesis-inspired structural rearrangement of Li and Na domains

(A and B) Schematics of interfacial structures of (A) pure Li and (B) Li-Na composite anodes during Li stripping at low stack pressure.
(C) Galvanostatic voltage profiles of various Li-Na composite electrodes during Li stripping at various stack pressures.
(D) Average stripped areal capacity of various Li-Na electrodes (three experiments each) at various stack pressures.
(E and F) Cryo-FIB-SEM images of Li-Na composite anode (10% Na) at various stages of cycling: (E) the initial state and (F) after 4 mAh cm^{-2} was stripped.
(G) Reaction current density at the Li-SSE interface with and without Na at time (t) = 0 and t = 2 min
(H) Long-term cycling stability of the 10% Na electrode.
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of Na domains fills the voids between the anode and the SSE.

To deepen the understanding of this morphogenesis and to support its industrial applications, further explorations can be considered on several fronts. (1) Interfacial reactions between Na and Li_6PS_5Cl, which may affect long-term interfacial stability, can be investigated.[8] For example, Becker et al. show that <1 mol % Na originating from impurity in the electrolyte can be detrimental to the Li-solid electrolyte interface.[9] A comprehensive investigation of the interphase would provide deeper insights into the interfacial stability and the robustness of this strategy. (2) Operation at high current densities can be examined. Most data in this study are obtained at or below 0.5 mA cm^{-2}, while 1–3 mA cm^{-2} is ideal for practical battery operation. A deeper understanding of the interplay among current density, stack pressure, and mechanochemical processes is essential to unlock the full potential of the morphogenic Li-Na composite electrode under realistic operating conditions.

In summary, Yoon et al. present a transformative design paradigm for ASSLBs: leveraging a soft, inactive metallic phase for self-regulating interfacial morphogenesis. This dynamic contact retention approach enables stable cycling at ultralow pressures, eliminating the need for brittle interlayers or complex fabrication. The strategy is scalable and adaptable, offering broad potential for advancing high-performance solid-state batteries. This study opens a new direction for stabilizing the Li metal anode in ASSLMBs under practical, low-pressure conditions.

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DECLARATION OF INTERESTS

The authors declare no competing interests.

REFERENCES

1. Gao, Z., Sun, H., Fu, L., Ye, F., Zhang, Y., Luo, W., and Huang, Y. (2018). Promises, challenges, and recent progress of inorganic solid-state electrolytes for all-solid-state lithium batteries. Adv. Mater. *30*, 1705702. https://doi.org/10.1002/adma.201705702.
2. Feng, X., Fang, H., Wu, N., Liu, P., Jena, P., Nanda, J., and Mitlin, D. (2022). Review of modification strategies in emerging inorganic solid-state electrolytes for lithium, sodium, and potassium batteries. Joule *6*, 543–587. https://doi.org/10.1016/j.joule.2022.01.015.
3. Banerjee, A., Wang, X., Fang, C., Wu, E.A., and Meng, Y.S. (2020). Interfaces and interphases in all-solid-state batteries with inorganic solid electrolytes. Chem. Rev. *120*, 6878–6933. https://doi.org/10.1021/acs.chemrev.0c00101.
4. Wang, C., Liu, Y., Jeong, W.J., Chen, T., Lu, M., Nelson, D.L., Alsaç, E.P., Yoon, S.G., Cavallaro, K.A., Das, S., et al. (2025). The influence of pressure on lithium dealloying in solid-state and liquid electrolyte batteries. Nat. Mater. *24*, 907–916. https://doi.org/10.1038/s41563-025-02198-7.
5. Zhang, J., Fu, J., Lu, P., Hu, G., Xia, S., Zhang, S., Wang, Z., Zhou, Z., Yan, W., Xia, W., et al. (2025). Challenges and strategies of low-pressure all-solid-state batteries. Adv. Mater. *37*, 2413499. https://doi.org/10.1002/adma.202413499.
6. Ning, Z., Li, G., Melvin, D.L.R., Chen, Y., Bu, J., Spencer-Jolly, D., Liu, J., Hu, B., Gao, X., Perera, J., et al. (2023). Dendrite initiation and propagation in lithium metal solid-state batteries. Nature *618*, 287–293. https://doi.org/10.1038/s41586-023-05970-4.
7. Yoon, S.G., Vishnugopi, B.S., Nelson, D.L., Yong, A.X.B., Wang, Y., Sandoval, S.E., Thomas, T.A., Cavallaro, K.A., Shevchenko, P., Alsaç, E.P., et al. (2025). Interface morphogenesis with a deformable secondary phase in solid-state lithium batteries. Science *388*, 1062–1068. https://doi.org/10.1126/science.adt5229.
8. Wan, H., Wang, Z., Zhang, W., He, X., and Wang, C. (2023). Interface design for all-solid-state lithium batteries. Nature *623*, 739–744. https://doi.org/10.1038/s41586-023-06653-w.
9. Becker, J., Weintraut, T., Benz, S.L., Fuchs, T., Lerch, C., Becker, P., Eckhardt, J.K., Henß, A., Richter, F.H., and Janek, J. (2025). Purity of lithium metal electrode and its impact on lithium stripping in solid-state batteries. Nat. Commun. *16*, 5395. https://doi.org/10.1038/s41467-025-61006-7.