



Toward practical anode-free lithium batteries through planar deposition and interphase engineering

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MAIN TEXT

The pursuit of higher energy density in rechargeable batteries has long motivated the exploration of lithium metal as an anode^[1,2]. Among the most radical configurations, anode-free lithium metal batteries (AFLMBs) stand out for their potential to maximize both gravimetric and volumetric energy density while simplifying manufacturing^[3,4]. However, the absence of excess lithium and host materials introduces severe interfacial instability, leading to poor cycling performance and limiting their practical relevance.

In this context, the recent work by Liu *et al.* represents a notable advance^[5]. The authors report a 500 Wh kg⁻¹-class anode-free pouch cell with extended cycle life, enabled by a carefully designed “crossover-coupled” electrolyte. At the core of this strategy lies a rethinking of interphase formation: rather than being a local, electrode-specific process, the solid electrolyte interphase (SEI) is shown to emerge from coupled chemical reactions involving species generated at both electrodes.

A key achievement of this work is the demonstration of highly reversible planar lithium deposition and dissolution. Conventional lithium metal systems typically exhibit three-dimensional growth and stripping, leading to morphological instability, dead lithium formation, and continuous SEI rupture. In contrast, Liu *et al.* show that their electrolyte promotes a two-dimensional, planar deposition mechanism, associated with synchronized stripping and minimal porosity^[5]. By microscopy analyses, they showed that lithium deposits exhibited dense, low-porosity structures (~ 1.6%) and maintained structural integrity during cycling, in stark contrast with reference electrolytes.

This behavior is enabled by the formation of a polymer-rich, B-F-based SEI with sub-nanometer uniformity and high mechanical flexibility. Unlike conventional inorganic-rich or bilayer SEIs, this interphase acts as a self-adaptive mesh that accommodates volume changes and maintains interfacial contact. Importantly, its homogeneous structure ensures uniform lithium-ion flux, which is critical to suppress localized deposition and enable planar growth. The result is a rare



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combination of high Coulombic efficiency, low dead lithium formation, and stable cycling even at high areal capacities (5.6 mAh cm^{-2}).

Equally significant is the mechanistic insight into the crossover-coupled interphase chemistry. Their study shows that reactive intermediates generated at the cathode and anode can migrate across the cell and participate in coupled reactions, leading to the formation of a polymeric SEI while simultaneously suppressing parasitic reactions such as gas evolution. Experimental evidence, including Nuclear Magnetic Resonance and Electron Paramagnetic Resonance, supports the presence of radical species on both electrodes and their role in interfacial chemistry. This challenges the traditional paradigm of independent SEI and Cathode Electrolyte Interphase formation and suggests that electrolyte design should be approached as a system-level problem.

From a practical standpoint, the reported performance is particularly compelling. The authors demonstrate a 2.7 Ah pouch cell with 508 Wh kg^{-1} and stable cycling for 100 cycles at full depth of discharge and up to 250 cycles at partial depth. These performances exceed most previously reported AFLMBs, which typically suffer from rapid capacity fade at high energy densities. Moreover, the absence of gas evolution and the reduced formation of inactive lithium species point to improved safety and efficiency.

Despite these advances, several challenges remain before widespread adoption can be envisioned. First, the cycle life, while impressive for anode-free systems, still falls short of commercial lithium-ion benchmarks^[6]. Extending durability beyond several hundred cycles without sacrificing energy density remains a critical objective. Second, the reliance on a specific electrolyte formulation raises questions about scalability, cost, and compatibility with existing manufacturing processes. The long-term chemical stability of the polymer-rich SEI under varied operating conditions also warrants further investigation.

More broadly, the concept of crossover-coupled chemistry opens new research directions, but also introduces additional complexity. Controlling cross-electrode transport and reaction pathways may be challenging in large-format cells or under fast charging conditions. Furthermore, the generality of this approach across different cathode chemistries and electrolyte systems remains to be demonstrated.

Nevertheless, this work represents an important step toward bridging the gap between laboratory demonstrations and practical anode-free batteries. By combining rigorous cell-level design with fundamental insights into interphase chemistry, Liu *et al.* provide a compelling blueprint for future developments^[5]. Their findings suggest that achieving stable lithium metal batteries may ultimately depend not only on materials innovation, but on a holistic understanding of coupled electrochemical processes across the entire cell.

DECLARATIONS

Authors' contributions

The author contributed solely to the article.

Availability of data and materials

Not applicable.

AI and AI-assisted tools statement

During the preparation of this manuscript, the AI tool ChatGPT (GPT-5-level model, released 2025-08-07) was used solely for language editing. The tool did not influence the study design, data collection, analysis, interpretation, or the scientific content of the work. All authors take full responsibility for the accuracy, integrity, and final content of the manuscript.

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Conflicts of interest

Bella, F. is an International Advisory Editorial Board Member of the journal *Energy Z*, but was not involved in any steps of editorial processing, notably including manuscript handling, and decision making. The author declares that he has no other conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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