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Current Collector Design for Lithium Metal Batteries: A Review

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Abstract. Compared to graphite-anode lithium-ion batteries, lithium metal batteries, with their ultra-high theoretical capacity and low potential, have become an important direction for next-generation high-energy-density energy storage systems. However, issues such as lithium dendrite growth, volume expansion, and unstable interfaces severely limit their practical application. As the substrate for lithium deposition, the structure and surface design of the current collector directly influence the nucleation and growth behavior of lithium. Researchers have effectively reduced local current density, achieved more uniform lithium deposition, and improved cycling stability by constructing three-dimensional porous structures, introducing lithiophilic modification layers, and optimizing gradient interfaces. This article systematically reviews the design strategies for metal-based and carbon-based current collectors, focusing on the effects of pore regulation, surface lithiophilic modification, and composite interface construction on electrochemical performance. Meanwhile, considering practical challenges, it prospects the optimization directions for current collectors that balance high areal capacity, long cycle life, and low cost, aiming to provide a reference for the practical application of lithium metal batteries.

Keywords: lithium metal battery, current collector, lithium dendrite, lithiophilic modification, electrochemical performance

1. Introduction

In recent years, lithium metal batteries (LMBs) have been considered as strong competitors for future high-energy-density storage systems, due to their extremely high theoretical energy density and low reduction potential. However, widespread commercialization is impeded by uncontrolled lithium dendrite growth, infinite volume expansion, and detrimental side reactions at the solid electrolyte interphase (SEI). All these challenges are directly linked to the lithium deposition behavior at the negative electrode/current collector interface [1-3]. As the initial substrate and conductive network for lithium deposition and stripping, the current collector's surface electric field distribution and ion-flux-guiding capabilities directly determine the severity of these issues. Therefore, the current collector design is the primary starting point for regulating lithium nucleation and growth behavior.

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Current collector design is no longer limited to simple conductive copper foil, continuously evolving toward functional frameworks. In A Roadmap for Solid-State Batteries, Schmaltz et al. [4] suggested that current collector design needs to address conductivity, mechanical stability, and interfacial compatibility. In solid-state batteries, the interfacial contact between the current collector and the electrolyte is one of the main issues [5-8]. Similarly, in Advancing Lithium Metal Batteries, Liu et al. summarized methods of using 3D-structured copper current collectors to control lithium nucleation [9], arguing that reducing local current density can effectively inhibit dendrite generation and thus improve cycle life. Zhang et al., in Developments, Novel Concepts, and Challenges of Current Collectors: From Conventional Lithium Batteries to All-Solid-State Batteries, reviewed the development of current collectors, from traditional liquid lithium-ion batteries to all-solid-state batteries and proposed that functional composite current collectors [10] (e.g., featuring lithiophilic coatings, porous frameworks, and polymer-metal hybrid structures) will be the future trend. Based on the above consensus, current research mainly focuses on the following strategies: the construction of 3D porous structures, surface lithiophilic chemical modification, and the synergistic design of composite interfaces. However, how to achieve large-scale production and long-term cycling stability remains a challenge.

In terms of 3D porous structure design, current research mainly revolves around the following directions. The first is constructing frameworks to disperse the local current density and accommodate volume expansion. Compared with conventional two-dimensional copper foils, porous copper foil can realize "bottom-up" lithium deposition owing to its 3D skeletal structure, thereby reducing the formation of "dead lithium" and improving Coulombic efficiency and cycling stability [11-14]. However, copper remains the dominant current collector material, inevitably suffering from poor lithiophilicity. At present, this issue is primarily addressed by introducing lithiophilic sites to lower the nucleation overpotential and thus induce uniform lithium deposition [15-17]. For instance, Sunil Kumar et al. employed a free-standing $Ti_3C_2T_x$-based current collector, which substantially improved the uniformity of deposition and cycling lifespan, demonstrating the advantage of 2D layered materials in modulating the interfacial electric field distribution [8, 18-25]. Additionally, designing alloying anodes represents another feasible strategy; in which metals such as magnesium and zinc thermodynamically promote preferential lithium nucleation due to their intrinsic lithiophilicity and structural stability, effectively suppressing dendrites [23, 26-31]. For anode-free configurations, extensive studies on surface functionalization (e.g., lithiophilic coatings and micro/nanostructure engineering) demonstrate that 3D porous frameworks substantially decrease initial lithium nucleation overpotential and reduce local current density [15, 32-38].

Although the above strategies are effective in laboratory stage, they still face challenges such as production and storage stability, storage stability, and structural changes during long-term cycling in practical applications and large-scale production. Therefore, a critical summary and reflection on existing design paradigms is necessary. This article focuses on reviewing practical current collector strategies, aiming to provide a theoretical reference for designing LMBs that balance capacity, lifespan, cost, and other factors.

2. Methods and analysis

2.1. Bibliometric methods

To map the research directions and trends in the field of current collector design for lithium metal batteries, this study employs bibliometric methods to quantitatively analyze academic output in this area. Data were sourced from the Web of Science database, and relevant articles were screened using

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search fields. The search strategy centered on lithium metal or lithium metal battery anodes, while limiting the concept of current collectors, and combined with recent research hotspots covering modification, engineering optimization, three-dimensional structures, lithiophilic hosts, porous structures, and surface/interface engineering as core modification strategies. The time span was the last ten years, and document types were Article/Review. The final number of valid articles analyzed was 1,352. VOSviewer was employed as the primary analysis tool to generate keyword co-occurrence networks, author/institution collaboration networks, and data clouds. Key statistical indicators evaluated include publication volume, citation frequency, country/institution contributions, and keyword frequency

2.2. Results and analysis

2.2.1. Publication and citation analysis

Based on the screened valid articles, the WOS database provided a two-week trend chart of research output scale and impact in this field. It can be seen from the Figure 1 that the output in fields related to lithium metal anodes was very low around 2014, with significant acceleration appearing between 2018 and 2019, and sustained stable growth after 2020. This reflects the increasing demand for the use of lithium metal battery anodes, and the design and optimization of current collectors have received widespread attention. In terms of research impact, it was almost zero in the early period (2014-2017), with a turning point in 2018. As the number of papers increased rapidly, it peaked in 2025, confirming that the field has entered a stage of high attention.

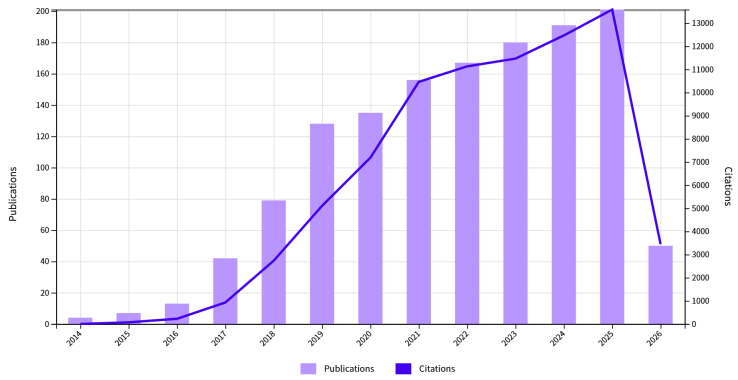


Figure 1. Annual publication and citation trends

2.2.2. Co-citation analysis

Using VOSviewer software for in-depth mining and visualization analysis of cited literature data, the citation threshold was set to 80 to screen hot articles in the field. The result yielded 83 cited references, and the statistical network diagram is shown below in Figure 2. Among them, lin dc (2017) was cited 576 times, yan k (2016) 450 times, and cheng xb (2017) 444 times. From the colors, the whole is divided into three clusters. Different colored clusters mainly represent different research topic groups divided by clustering algorithms. The red cluster mainly represents the development history of lithium metal batteries and their problems; the green cluster mainly represents current collector modification strategies for lithium metal batteries to regulate lithium ion deposition behavior; the blue cluster mainly represents the status and improvement directions of lithium metal anodes.

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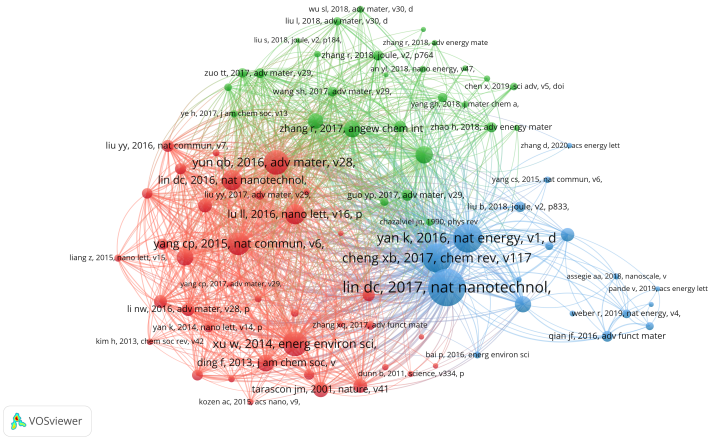


Figure 2. Co-citation network of references

3. Challenges

3.1. Lithium dendrite growth

The growth of lithium dendrites is mainly divided into three stages. First, lithium metal reacts with the electrolyte to form a solid electrolyte interphase (SEI) layer on the negative electrode surface. Next, lithium ions nucleate and aggregate on the electrode surface, forming crystal nuclei as the starting point for subsequent dendrite growth. Finally, lithium metal grows along the crystal nuclei, piercing the SEI layer to form irregular lithium dendrite structures. This non-uniform growth significantly increases the specific surface area, leading to aggravated side reactions and accumulation of "dead lithium", severely affecting the Coulombic efficiency and cycling stability of the battery [39-41].

3.2. Structural defects of copper current collectors

In lithium batteries, copper foil is widely used as a current collector due to its good electronic conductivity and relative low cost [42]. However, its inherent physical and chemical defects significantly exacerbate the above-mentioned lithium dendrite growth process. The surface of copper current collectors often has physical defects such as scratches and oxide layers, as well as low lithiophilicity, which cause lithium ions to need to overcome a large nucleation overpotential during the initial deposition stage. A high nucleation overpotential encourages lithium to preferentially nucleate in local high-current-density regions, forming isolated crystal nuclei instead of a uniform film. These crystal nuclei then become the starting points for dendrite growth, with lithium metal growing rapidly along the nuclei and piercing the SEI layer to form irregular dendrite structures [3, 43].

Moreover, during repeated deposition and stripping, metallic lithium undergoes a huge volume expansion of nearly 300%, and the resulting mechanical stress concentrates at the current collector interface. If the copper foil is excessively thinned (down to hundreds of nanometers) to pursue high energy density, its mechanical strength cannot withstand this cyclic stress, leading to dendrites or lithium whiskers to penetrate the collector and cause complete interface failure. Meanwhile, dendrite fragments that detached during stripping process from "dead lithium" (Figure 3), further hindering ion transport and exacerbating polarization. In solid-state electrolyte systems, even if the copper

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current collector does not directly contact the sulfide electrolytes, its chemical instability still easily causes corrosion, destroying interface stability and indirectly promoting non-uniform dendrite growth.

In summary, the core dilemma of the copper current collector is that its original electronic conductivity, surface chemical properties (lithiophobicity and defects), and mechanical ductility cannot simultaneously meet the multi-dimensional requirements of uniform nucleation, dendrite-free deposition, corrosion resistance, and buffering volume expansion. These defects collectively act on the nucleation and growth stages of lithium dendrites, forming a vicious cycle of 'defect-induced non-uniform nucleation → rapid dendrite growth → repeated SEI rupture and dead lithium accumulation'. Therefore, modification research based on copper current collectors mainly focuses on the following directions: constructing lithiophilic nucleation sites via surface alloying to reduce nucleation overpotential; designing three-dimensional porous structures to accommodate volume changes and disperse local current density; or introducing an elastic buffer interlayer to release interface stress and isolate side reactions, thereby achieving uniform and dense lithium deposition and inhibiting dendrite growth [14, 37, 44-47].

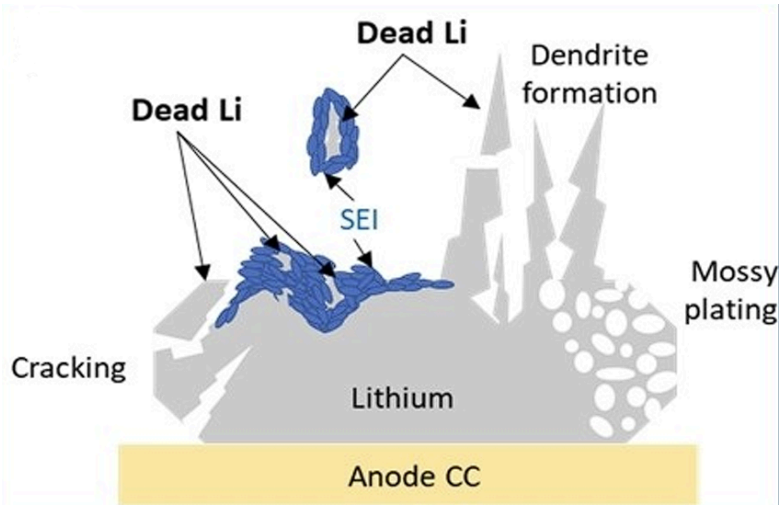


Figure 3. Schematic diagram of dead lithium formation

3.3. Current collector design strategies

With the deepening of research, the focus has gradually shifted from single-material modifications to the synergistic interplay among "structure, composition, and interface," aiming to realize safe, long-lasting, and high-energy-density LMBs. Figure 4 illustrates several modification strategies for current collectors, including organic and inorganic coating as well as alloyed anodes. Based on the above discussion, researchers have developed multi-level modification strategies focused on reconstructing the surface chemistry and 3D spatial architecture of current collectors. Yu Xiaoliang, Chen Guohua, and colleagues demonstrated that structural design can effectively reduce the local current density and suppress dendrites by regulating the collector's microstructure and surface chemistry [48].

Surface coating is the most direct method for copper's surface defects. Functional films providing lithiophilicity, ionic conductivity, and mechanical flexibility are constructed via physical coating, electrodeposition, or chemical self-assembly. Organic coatings, such as polydopamine or organosilane films are rich in polar functional groups which can induce uniform distribution of lithium-ion flux [21]. Their inherent flexibility can also buffer deposition stress and effectively

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block the copper substrate from electrolyte corrosion. However, the inherently low ionic conductivity of some organic layers may restrict rate performance, so inorganic coatings are more widely used. Carbon-based materials with high specific surface area and conductivity, such as vertical graphene, nitrogen-doped graphene, or carbon nanotube sponges, can be directly grown on copper foil. Their porous frameworks not only disperse local current density but also greatly reduce the lithium nucleation overpotential through lithiophilic heteroatom sites such as pyridinic nitrogen and pyrrolic nitrogen on the pore walls, guiding lithium metal to uniformly fill the three-dimensional space rather than forming dendritic protrusions on a two-dimensional plane [49-52].

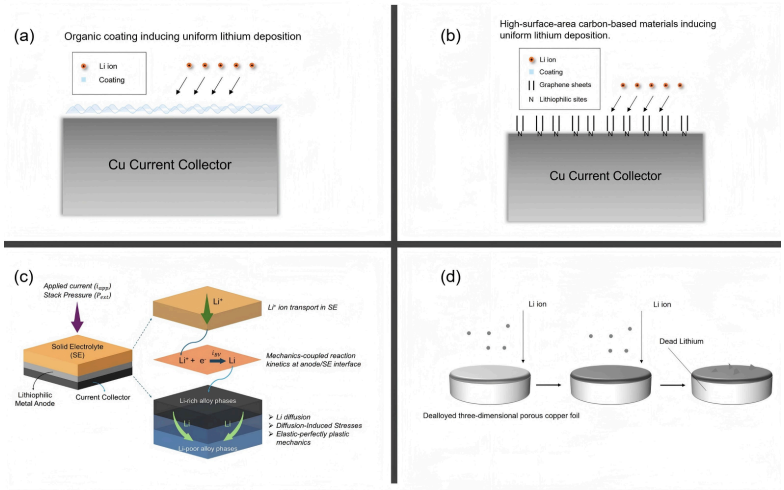


Figure 4. (a) Organic coating inducing uniform lithium deposition (b) High-surface-area carbon-based materials inducing uniform lithium deposition. (c) Key Electrochemical Mechanisms of Alloying Anodes. Adapted from Chatterjee et al.(d) Schematic of Li deposition

Metal modification layers utilize elements like gold, silver, zinc, magnesium, and tin—which alloy with lithium or offer favorable lattice matching—to create isolated lithiophilic islands or continuous films on the copper [53-55]. These alloy sites have a strong chemical affinity for lithium atoms, partially eliminating the nucleation barrier and enabling lithium deposition to proceed in a two-dimensional spreading and planar epitaxial growth manner from the beginning, forming a dense bulk rather than mossy dendrites [13, 56, 57]. To combine the flexibility of organics with the conductivity and lithiophilicity of inorganics/metals, composite coatings have been developed. For instance, wrapping silver nanoparticles in polydopamine and compositing them with graphene oxide yields an artificial SEI that anchors initial nucleation via the silver sites while regulating ion flux through the graphene; simultaneously, the polydopamine accommodates interfacial volume fluctuations [50, 58]. Furthermore, in-situ growth techniques directly synthesize copper-based arrays (e.g., cuprous oxide nanosheets or copper oxide nanopillars) on the foil via thermal oxidation or wet chemistry. These arrays undergo conversion reactions with depositing lithium, creating a composite interface rich in lithium oxide and copper nanocrystals seamlessly bonded to the substrate, providing abundant nucleation sites and vertical ion-transport channels.

Although two-dimensional materials have advantages in preventing electrode pulverization, promoting lithium ion transport between the electrolyte and electrode interface, and optimizing lithium ion deposition [59], they often fail to accommodate extreme volume changes at high rates, making 3D current collectors an inevitable choice [12, 60]. Through chemical dealloying, electrochemical etching, or templating, planar copper is transformed into a micro/nanoporous framework to prevent current density concentration [42]. Wang et al. demonstrated a periodic

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conductive-dielectric layered structure (PAN/CNF) under harsh conditions of 3 mA cm^{-2}, 3 mAh cm^{-2}; the symmetric cell cycled stably for 835 cycles with an overpotential of only 52 mV, far exceeding pure PAN (400 cycles) and pure CNF (122 cycles) [61]. Such high-surface-area structures inherently dilute local current density, allowing lithium ion flux to be fully dispersed within the framework. While the interconnected internal pores serve as pre-set lithium storage cavities, confining the huge volume expansion inside the framework rather than pushing it outward to the electrode level, thus maintaining macroscopic dimensional stability. Further constructing secondary structures such as lithiophilic zinc, silver metal layers, or cobalt oxide nanosheets on the surface of these three-dimensional copper frameworks can create a lithiophilic gradient, inducing ordered bottom-up lithium deposition, fundamentally preventing premature top dendrite formation and continuous electrolyte consumption [62, 63]. In addition, Li et al., in *Advanced Polymer Materials for Protecting Lithium Metal Anodes of Liquid-State and Solid-State Lithium Batteries*, proposed a strategy of using cellulose materials to modify battery components, including separators, electrolytes, and current collectors. This material can not only reduce the weight of batteries, but also significantly improve their performance and cycling life, which can also serve as one of the future research directions [64-68].

Ultimately, these modification strategies share three core objectives: homogenizing lithium-ion flux, providing abundant low-energy nucleation sites, and securing physical space for volume changes. They systematically pave the way for dendrite inhibition and interface stabilization, spanning from precise chemical tuning to macroscopic 3D reconstruction [5-8, 69, 70]. Table 1 summarizes the performance data of modified batteries.

Table 1. Battery performance of several current collectors for lithium metal batteries

Modification Strategies	Current (mA cm^{-2})	CE/lifespan (%/cycles)
3D porous Cu/Li metal composite anode [71]	0.5	96/150
Dealloying 3D porous current collector [72]	0.5	97/250
Organic coating [73]	1.0	95/200
Carbonbased lithiophilic coating [74]	1.0	98.5/600
Gradient composite interface [11]	3.0	98.1/835
Lightweight functional scaffold [75]	0.5	99.5/350

4. Conclusion and outlook

Current research has reached a consensus: the key to current collector design lies in synergizing interface lithiophilic modification and three-dimensional structural reconstruction to transform lithium deposition behavior from uncontrolled dendrite growth into uniform, dense planar or spatial filling. Strategies such as organic/inorganic coatings, metal alloying modification, and in-situ grown copper-based compounds can significantly reduce the nucleation overpotential and provide abundant lithiophilic sites. Porous frameworks constructed by chemical dealloying, electrochemical etching, and template methods disperse current density geometrically and provide buffer space for volume expansion. The introduction of composite gradient interfaces further achieves ordered bottom-up lithium deposition. However, most of these strategies remain at the laboratory verification stage. Future research needs to achieve breakthroughs in the following directions: clarifying the quantitative structure–property relationship between porosity/pore size distribution and electrochemical performance to guide industrial-scale controllable preparation; developing ultra-thin

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composite artificial interface layers with both high ionic conductivity and mechanical flexibility; using in-situ characterization techniques to dynamically reveal the microscopic mechanisms of lithium nucleation and interface failure; and simultaneously systematically integrating advanced current collector design concepts with anode-free configurations and solid-state electrolyte systems to promote the practical application of high-energy-density lithium metal batteries.

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