Three-dimensional lithiophilic Cu@Sn nanocones for dendrite-free lithium metal anodes

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ABSTRACT The uneven deposition of lithium (Li) on current collectors causes serious dendrite growth and volume expansion. Commercial foamed copper (Cu) current collectors are unsuitable for Li anodes because of their large volume and mass and lithiophobic nature. Herein, a three-dimensional (3D) copper@tin (Cu@Sn) nanocone current collector with small volume, light weight, and lithiophilic nature was prepared by a simple electrodeposition method. The synergy of the nanoconical structure and lithiophilic Sn promotes the even deposition of Li and effectively inhibits the formation of Li dendrites. The resultant half batteries exhibit high Coulombic efficiency of 97.6% after 100 cycles at 1 mA cm⁻², and the symmetrical Li battery demonstrates a prolonged lifespan of over 600 h at 1 mA cm⁻². The full battery based on organic liquid electrolyte with LiFePO₄ also exhibits a long lifespan of 550 cycles with high capacity retention of 95.1% at 1 C. Moreover, 3D Cu@Sn nanocone-based solid-state batteries exhibit excellent electrochemical performance and show no decay after 500 cycles at 1 C. Our work provides a strategy for fabricating 3D current collectors for high-energy-density Li metal batteries.

Keywords: lithium metal anode, current collector, 3D structure, lithiophilic, Cu@Sn nanocones

INTRODUCTION

Lithium (Li) metal is deemed the “holy grail” anode owing to its high theoretical specific capacity (3860 mA h g⁻¹) and low negative potential (−3.04 V vs. standard hydrogen electrode) [1–3]. Li metal anode-based batteries, such as Li–S and Li–O₂/CO₂ batteries, can be used as high-energy-density battery systems to meet the requirements of electric vehicles [4–8]. However, volume change during Li plating/stripping processes and the existence of Li dendrites in Li metal anodes impede their applications [9,10]. Thus, the use of Li metal anodes in-

duces low Coulombic efficiency (CE) and may result in a short circuit of the battery and even cause fire or explosion [11,12].

Considerable effort has been undertaken to address these issues of Li metal anodes, such as the use of electrolyte additives [13–15], artificial solid electrolyte interface (SEI) films [16–18], solid-state electrolyte [19–21], and three-dimensional (3D) current collectors [22–24], all of which have yielded significant results. Among them, the 3D current collector can effectively suppress Li dendrites and its 3D structure can also serve as a host for Li deposition and mitigate volume expansion during cycling [25–27]. However, commercially available metal foam skeletons, such as copper (Cu) and nickel (Ni) foams, are not particularly suitable for Li metal batteries (LMBs) owing to their large volume and mass, which can decrease the energy density of the battery [28,29]. Furthermore, the weak interaction among Cu, Ni, and Li causes the uneven deposition of Li and generates Li dendrites [30,31]. Therefore, the modification of a lithiophilic material is necessary for current collectors using approaches such as atomic layer deposition (ALD) of ZnO and Al₂O₃, which improve the affinity between current collectors and Li [32,33] but typically require specialized equipment and high cost. Thus, the direct modification of planar Cu foil using an economical and simple method for preparing 3D lithiophilic Cu current collector is essential for practical use.

Herein, a 3D copper@tin (Cu@Sn) nanocone current collector with small volume, light weight, and lithiophilic characteristics was prepared using a simple electrodeposition approach to grow Sn-modified Cu nanocone array on a planar Cu foil. The 3D structure of the Cu@Sn nanocones can facilitate uniform electric field and the dispersion of current density. Moreover, Sn can react with Li to form Li–Sn alloy, and act as the initial Li nucleation

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sites to enable even deposition of Li. The synergy of 3D nanoconical structure and lithiophilic Sn promotes the uniform deposition of Li and effectively inhibits Li dendrites. Thus, CEs of 97.6% and 96.6% were maintained after 100 and 250 cycles at current densities of 1 and 0.5 mA cm^{-2} , respectively. The assembled Li|Li symmetrical battery based on Cu@Sn nanocones exhibited a prolonged lifespan (600 h at 1 mA cm^{-2}). The liquid full battery Li/Cu@Sn|LiFePO₄ (LFP) maintained capacity retention of 95.1% after 550 cycles at 1 C. Furthermore, a polyvinylidene fluoride–hexafluoropropylene-based solid electrolyte (PVDF–HFP–5 wt% SiO₂) was prepared and a solid-state full battery Li/Cu@Sn|PVDF–HFP–5 wt% SiO₂|LFP was assembled to determine the electrochemical performance of the Cu@Sn nanocones in the solid-state battery. Results indicated excellent cyclic stability of the battery in which the discharge capacity showed no decay after 500 cycles at 1 C. The use of the Cu@Sn nanocone current collector and solid-state electrolyte is expected to further improve and ensure safe performance of batteries more suitable for commercial applications.

EXPERIMENTAL SECTION

Chemicals and materials

All reagents used in this study were of analytical grade and used without further treatment. Copper sulfate (CuSO₄·5H₂O, 99%) and nickel sulfate (NiSO₄·6H₂O, 99.9%) were purchased from Macklin (Shanghai, China). Sodium hypophosphite (NaH₂PO₂, 99%) was acquired from Innochem (Beijing, China). Sodium citrate (Na₃C₆H₅O₇·2H₂O, 99%) was obtained from Heowns (Tianjin, China). Polyethylene glycol (PEG, molecular weight = 2000), boric acid (H₃BO₃, 99.99%), sodium hydroxide (NaOH), stannous sulfate (SnSO₄), PVDF–HFP, and fumed nano-SiO₂ were purchased from Aladdin (Shanghai, China).

Fabrication of the Cu@Sn nanocones

Synthesis of the Cu nanocones

Cu foil was soaked in $0.5 \text{ mol L}^{-1} \text{ H}_2\text{SO}_4$, acetone, and absolute ethanol for 30 min, washed with ultrapure water, and dried in a vacuum oven at 60°C for 12 h. A 100-mL aqueous solution was prepared using $0.03 \text{ mol L}^{-1} \text{ CuSO}_4\cdot 5\text{H}_2\text{O}$, $0.0024 \text{ mol L}^{-1} \text{ NiSO}_4\cdot 6\text{H}_2\text{O}$, $0.24 \text{ mol L}^{-1} \text{ NaH}_2\text{PO}_2$, $0.05 \text{ mol L}^{-1} \text{ Na}_3\text{C}_6\text{H}_5\text{O}_7$, $0.5 \text{ mol L}^{-1} \text{ H}_3\text{BO}_3$, and 6 g L^{-1} PEG, and its pH was adjusted to 8.0 using NaOH. Electrodeposition was performed at a potential of -1.12 V at 75°C for 30 min using the treated Cu foil, Pt

sheet, and saturated Ag/AgCl as the working, counter, and reference electrodes, respectively. The deposited Cu foil was soaked in $0.1 \text{ mol L}^{-1} \text{ H}_2\text{SO}_4$ for 1 h, rinsed with ultrapure water, and dried in a vacuum oven at 60°C.

Fabrication of the Cu@Sn nanocones

A 100-mL aqueous solution was prepared using $2 \text{ mol L}^{-1} \text{ NaOH}$, $0.1 \text{ mol L}^{-1} \text{ Na}_3\text{C}_6\text{H}_5\text{O}_7$, and $0.05 \text{ mol L}^{-1} \text{ SnSO}_4$. Electrodeposition was performed at a current density of 3.3 mA cm^{-2} for varying time periods using the Cu nanocones, Pt sheet, and saturated Ag/AgCl as the working, counter, and reference electrodes, respectively. The obtained Cu@Sn nanocones were washed with ultrapure water and dried in a vacuum oven at 60°C.

Preparation of the PVDF–HFP-based polymer electrolyte

PVDF–HFP (2.0 g) and nano-SiO₂ particles were dispersed in 15 mL acetone and stirred at 50°C for 2 h to obtain homogenous viscous liquids. To obtain a polymer electrolyte membrane, the viscous liquids were scraped onto an Al foil and dried in a vacuum oven at 100°C for 12 h. The membrane was cut into small pieces with 16-mm diameter and soaked in $1 \text{ mol L}^{-1} \text{ Li bis(trifluoromethanesulfonyl) imide (LiTFSI)}$ in 1,3-dioxolane (DOL) and 1,2-dimethoxyethane (DME) (volume ratio = 1:1) with 1% LiNO₃ for 24 h.

Electrochemical measurements

CR2032 coin batteries were assembled using the Cu foil or 3D Cu@Sn nanocones and Li metal foil as the working and counter electrodes, respectively, Celgard 2400 microporous polypropylene film as the separator, and 60 μL of $1 \text{ mol L}^{-1} \text{ LiTFSI}$ in DOL/DME (volume ratio = 1:1) with 1% LiNO₃ as the electrolyte. All batteries were assembled in an argon (Ar)-filled glove box and tested on a multichannel battery tester (Land 2001A Battery Testing System) at 25°C. For the CE test, a fixed amount of Li (1 mA h cm^{-2}) was deposited on the current collector and then stripped away up to 1 V at 0.5 or 1 mA cm^{-2} for each cycle. Further, the batteries were cycled at 1 mA cm^{-2} for varying time periods to characterize the morphology of the deposited Li on the Cu foil or Cu@Sn nanocones. For the symmetrical battery test, Li (3 mA h cm^{-2}) was first deposited on the Cu foil or 3D Cu@Sn nanocones at 1 mA cm^{-2} . Then, the symmetrical batteries were charged/discharged at 1 mA cm^{-2} for 1 h in each half-cycle. Then, the liquid full battery was assembled using LFP as the cathode, Cu foil or 3D Cu@Sn nanocones with predeposited Li (3 mA h cm^{-2}) at 1 mA cm^{-2} as anodes, Celgard 2400 as the separator, and $1 \text{ mol L}^{-1} \text{ LiTFSI}$ in

DOL/DME (volume ratio = 1:1) with 1% LiNO_3 as the electrolyte. Thereafter, the solid-state full battery was assembled using LFP as the cathode, 3D Cu@Sn nanocones with predeposited Li (3 mA h cm^{-2}) at 1 mA cm^{-2} as the anode, and PVDF-HFP-based polymer as the electrolyte. The LFP electrolyte was prepared using a conventional doctor blade casting method. LFP, PVDF, and super P (mass ratio = 8:1:1) were mixed and dispersed in *N*-methyl-2-pyrrolidone (NMP) to achieve a homogeneous slurry. Then, the slurry was scraped onto the aluminum foil and dried in a vacuum drying oven at 80°C for 12 h. The average mass loading of LFP in the electrode was approximately 2.5 mg cm^{-2} . The full batteries were galvanostatically cycled between 2.4 and 4.0 V at 1 C.

Characterization

The morphology of the 3D Cu@Sn nanocones and Li deposition was observed using field-emission scanning electron microscopy (SEM, JEOL JSM-7500F) and scanning transmission electron microscopy (TEM) with elemental mapping recorded on FEI TALOX F200X G2. The contact angle was tested using a contact angle tester (TBU 100). The crystalline structures of the Cu foil, Cu nanocones, and Cu@Sn nanocones were characterized using powder X-ray diffraction (XRD, Rigaku MiniFlex600, Cu K α radiation).

RESULTS AND DISCUSSION

A schematic illustration of the synthesis of the Cu@Sn nanocones is shown in Fig. 1a [34]. The Cu nanocones were prepared *via* electrodeposition at -1.12 V *versus* saturated Ag/AgCl for 30 min and soaked in $0.1 \text{ mol L}^{-1} \text{ H}_2\text{SO}_4$ for 1 h. Compared with the planar Cu foil (Fig. S1a, b), the surface of the Cu nanocones became tarnished after modifying the nanocones on the Cu foil (Fig. S1c). The SEM image (Fig. S1d) shows a rough surface covered with a dense and uniform nanocone array. The Cu@Sn nanocones were prepared *via* electrodeposition at 3.3 mA cm^{-2} to modify Sn on the Cu nanocones. The Cu@Sn nanocones with varying Sn contents were prepared by tuning the deposition time. As shown in Fig. S2a–f, the Cu@Sn nanocones maintain conical structure and no bulk Sn was observed on the surface when the deposition time was 20 s. However, a small amount of bulk Sn appeared on the surface of the nanocones when the deposition time was 40 s, and more bulk Sn appeared with an increase in the deposition time, which hindered the uniform nucleation of Li. Thus, the deposition time of Sn was set to 20 s.

Figure 1 (a) Schematic illustration of the synthesis of the Cu@Sn nanocones. Top view (b) and cross-sectional (c) SEM images of the Cu@Sn nanocones. TEM elemental mapping (d) and high-resolution TEM image (e) of the Cu@Sn nanocones.

Fig. S3 shows the XRD patterns of the Cu foil, Cu nanocones, and Cu@Sn nanocones. The Cu foil and nanocone patterns show main peaks for Cu (JCPDs No. 04-0836), and a similar XRD pattern can be observed for the Cu@Sn nanocones. The characteristic peaks of Sn cannot be observed in the XRD pattern of Cu@Sn nanocones, which can be attributed to its low quantity below the instrument detection limit. Fig. 1b–e show the characterization of the Cu@Sn nanocones with deposition time of 20 s.

Fig. 1b shows that the nanocone array is distributed on the surface of Cu foil. The thickness of the Cu@Sn nanocone current collector was approximately 20 μm, and the nanocone array maintained good contact with the Cu foil (Fig. 1c), ensuring rapid electron transmission. TEM and mapping (Fig. 1d) results show that the Sn nanoparticles were evenly distributed on the nanocone surface, ensuring uniform nucleation sites. Furthermore, the high-resolution TEM image (Fig. 1e) shows an ordered crystal structure inside the nanocone with a lattice spacing of 0.208 nm, ascribed to the Cu (111) plane; the outer lattice of the nanocone can be observed with a lattice spacing of 0.279 nm, corresponding to the Sn (101) plane [30],

which confirms the distribution of Sn nanoparticles on the Cu nanocone surface.

The contact angles of the planar Cu foil and Cu@Sn nanocones with the electrolyte (1 mol L⁻¹ LiTFSI in DOL/DME (volume ratio = 1:1) + 1% LiNO₃) were tested (Fig. S4). The electrolyte could not completely spread on the planar Cu foil with a contact angle of 31.57°. However, it could quickly expand on the Cu@Sn nanocone current collector, indicating improved wetting ability of the Cu@Sn nanocone current collector toward the electrolyte, which allows the rapid diffusion and uniform nucleation of Li ions. Moreover, the deposition behavior of Li on the Cu foil and Cu@Sn nanocones was investigated at a current density of 0.5 mA cm⁻². Fig. 2 shows the morphology of Li deposited on the Cu foil and Cu@Sn nanocones under different deposition amounts (0.5, 1.0, and 2.0 mA h cm⁻²). Fig. 2a–c show the formation of dendritic Li on the Cu foil surface, and the dendritic morphology becomes more evident with an increase in the deposition amount. Dendritic Li may pierce the separator and cause a short circuit of the battery. Uniform granular Li was generated on the Cu@Sn nanocones rather than dendritic Li, and a relatively flat surface was formed with an increase in the deposition amount. This observation was mainly attributed to the initially formed small Li dendrite tip, which acts as the charge center in the electric field, continuously accumulating charges, and Li deposited on these sharp tips amplified the Li dendrite growth. Conversely, the 3D structure of the Cu@Sn nanocones dispersed the electric field distribution, improving the uniformity of the charge distribution and promoting the uniform deposition of Li. Further, the uniform distribution of Sn on the nanocones can form uniform initial Li nucleation sites and regulate Li deposition. Consequently, a relatively uniform and flat Li deposition plane was formed under the synergy of the

Figure 2 Morphology of Li deposited on the Cu foil and Cu@Sn nanocones at current densities of (a, d) 0.5 mA h cm⁻², (b, e) 1 mA h cm⁻², and (c, f) 2 mA h cm⁻² on the Cu foil (a–c) and Cu@Sn nanocones (d–f).

nanocone structure and Sn.

The interface energy between Li and the current collector determines the nucleation overpotential of Li on the current collector. Fig. 3 shows the voltage curve of Li deposited on the Cu foil, Cu nanocones, and Cu@Sn nanocones at a current density of 1 mA cm⁻². The figure shows a large nucleation overpotential of 240 mV (vs. Li⁺/Li) when Li was deposited on the planar Cu foil and a reduced nucleation overpotential of 211 mV (vs. Li⁺/Li) on the Cu nanocones. However, after modification using Sn, the nucleation overpotential of Li deposited on the Cu@Sn nanocones significantly reduced and was considerably lower than that of the Cu foil and Cu nanocones. The 3D structure possesses a large surface area, which can reduce the local current density, thereby decreasing the Li nucleation overpotential. Besides, Li ions first react with Sn to form Li–Sn alloys owing to the modification with Sn [35–37], which provides numerous active sites to promote Li nucleation [38,39]. Thus, the deposition of Li on Cu@Sn nanocones exhibited a lower nucleation overpotential than on Cu foil and Cu nanocones.

To investigate the plating/stripping behavior of Li on the Cu foil and Cu@Sn nanocones, Li/Cu and Li/Cu@Sn half batteries were assembled using 1 mol L⁻¹ LiTFSI in DOL/DME (volume ratio = 1:1) and 1% LiNO₃. Fig. 4a shows the CEs of the Cu foil and Cu@Sn nanocone electrodes cycled at a current density of 0.5 mA cm⁻² with an areal capacity of 0.5 mA h cm⁻². The CE of the planar Cu foil started to decrease and became unstable after 180 cycles; the CE was only 56.8% after 250 cycles. The CE of the Cu@Sn nanocones was stable at 96.9% after 250 cycles, which was considerably higher than that of the Cu foil. At a current density of 1 mA cm⁻² with an areal

Figure 3 Voltage curves of Li deposited on the Cu foil, Cu nanocones, and Cu@Sn nanocones at a current density of 1 mA cm⁻².

Figure 4 CEs of Li deposited on the Cu foil and Cu@Sn nanocone electrodes at current densities of (a) 0.5 and (b) 1 mA cm⁻². (c) Voltage profiles of Li plating/stripping on the Cu@Sn nanocones during the 50th, 100th, and 200th cycles at a current density of 0.5 mA cm⁻². (d) Voltage profiles of Li plating/stripping on the Cu@Sn nanocones and Cu foil at the current density of 0.5 mA cm⁻². (e) Li symmetrical battery (predeposited Li at 3 mA h cm⁻²) based on the Cu foil and Cu@Sn nanocones at the current density of 1 mA cm⁻² under the areal capacity of 1 mA h cm⁻².

capacity of 1 mA h cm⁻², the CE of the Cu foil was only 81.2% after 100 cycles and that of the Cu@Sn nanocones remained at 97.6% (Fig. 4b), because the Li dendrites generated on the Cu foil may fall from the root and become dead Li after losing electrical contact during the stripping process, which reduces the CE of the battery. However, the Cu@Sn nanocones can effectively suppress Li dendrites, thus ensuring high CE. Fig. 4c shows the voltage profiles of Li plating/stripping on the Cu@Sn nanocones during the 50th, 100th, and 200th cycles at the current density of 0.5 mA cm⁻² with an areal capacity of 0.5 mA h cm⁻². The almost overlapped charge/discharge curves indicate the excellent cycling stability of the Cu@Sn nanocones and show smaller voltage hysteresis than those of the Cu foil (Fig. 4d). The smaller voltage hysteresis of the Cu@Sn nanocones can be attributed to the large specific surface area and good wettability with liquid electrolyte to ensure rapid Li-ion transmission. To further investigate the stability of the Cu@Sn nanocone

current collector during cycling, symmetrical batteries were assembled. The polarization voltage of the Cu@Sn nanocone-based battery was approximately 10 mV at the current density of 1 mA cm⁻² and could stably cycle for more than 600 h (Fig. 4e). However, the Cu foil-based battery started to become unstable after 350 h, and its polarization voltage began to sharply increase after 400 h. These results indicate the excellent stability of the Cu@Sn nanocones during prolonged cycling.

To evaluate the application of the Cu@Sn nanocones in batteries, the Cu foil and Cu@Sn nanocones with predeposited Li (3 mA h cm⁻²) as the anodes and LFP as the cathode were used to assemble full batteries, correspondingly denoted as Li/Cu|LFP and Li/Cu@Sn|LFP. Fig. 5a, b demonstrate the galvanostatic charge/discharge voltage curves of Li/Cu|LFP and Li/Cu@Sn|LFP at 1 C from 2.4 to 4.0 V. The Li/Cu@Sn|LFP battery showed a smaller overpotential than the Li/Cu|LFP battery. The initial discharge capacity of the Li/Cu@Sn|LFP battery

Figure 5 Galvanostatic charge/discharge voltage profiles of the Li/Cu|LFP (a) and Li/Cu@Sn|LFP (b) batteries at 1 C from 2.4 to 4.0 V. (c) Cyclic performances of the Li/Cu|LFP and Li/Cu@Sn|LFP batteries at 1 C. (d) Galvanostatic charge/discharge voltage profiles of the solid-state battery at room temperature at 1 C from 2.4 to 4.0 V. (e) Cyclic performance of the solid-state battery at 1 C.

was 152.2 mA h g⁻¹ with 95.1% capacity retention after 550 cycles. However, the initial discharge capacity of the Li/Cu|LFP battery was 147.2 mA h g⁻¹ with only 86.2% capacity retention after 550 cycles. Fig. 5c shows the long cycle performance of the Li/Cu|LFP and Li/Cu@Sn|LFP batteries at 1 C. The Li/Cu@Sn|LFP battery showed better cycle stability than the Li/Cu|LFP battery, and the discharge capacity did not significantly decay after 550 cycles.

The Cu@Sn nanocones could suppress Li dendrites and improve the safety performance of liquid batteries. However, the safety hazards associated with the use of liquid electrolytes are still inevitable. Thus, a PVDF-HFP-5 wt% SiO₂ solid-state electrolyte was prepared, and the application of the Cu@Sn nanocones current collector in solid-state batteries was investigated. The use of a solid-state electrolyte and Cu@Sn nanocones is expected to further improve the safety performance of batteries. The

impedance of PVDF-HFP-5 wt% SiO₂ soaked in 1 mol L⁻¹ LiTFSI in DOL/DME (volume ratio = 1:1) with 1% LiNO₃ at room temperature was evaluated (Fig. S5), and the ion conductivity at room temperature was found to be 2.07×10^{-4} S cm⁻¹. The Cu@Sn nanocones with predeposited Li (3 mA h cm⁻²) as the anode and LFP as the cathode with the PVDF-HFP-5 wt% SiO₂-based electrolyte were used to assemble the full solid-state batteries (Li/Cu@Sn|PVDF-HFP-5 wt% SiO₂|LFP), and the electrochemical performance of the Cu@Sn nanocones in solid-state batteries was tested at room temperature. Fig. 5d demonstrates the galvanostatic charge/discharge voltage profiles of Li/Cu@Sn|PVDF-HFP-5 wt% SiO₂|LFP at 1 C from 2.4 to 4.0 V, in which the initial discharge capacity was 145.2 mA h g⁻¹ and the discharge capacity did not undergo decay after 500 cycles. Fig. 5e shows the long cycle performance of the Li/Cu@Sn|PVDF-HFP-5 wt% SiO₂|LFP batteries at 1 C.

The solid-state batteries exhibited excellent cyclic stability (Fig. 5e), which was comparable to that of liquid batteries.

CONCLUSIONS

The 3D Cu@Sn nanocones with small volume, light weight, and lithiophilic characteristics were prepared on the planar Cu foil by an electrodeposition method. The nanocone structure can disperse the current density, which improves the uniformity of the electric field distribution and promotes the uniform deposition of Li. Moreover, Sn can react with Li to form a Li–Sn alloy, forming numerous Li active sites and regulating Li deposition. The synergy of the nanocone structure and Sn effectively inhibits the formation of Li dendrites. The Li/Cu@Sn battery exhibits a high CE of 97.6% after 100 cycles at the current density of 1 mA cm^{-2} . The symmetrical battery can stably cycle for more than 600 h at the current density of 1 mA cm^{-2} . The liquid full battery Li/Cu@Sn|LFP exhibits excellent cyclic stability, and the capacity retention was maintained at 95.1% after 550 cycles. Moreover, the Cu@Sn nanocone current collector exhibits excellent electrochemical performance in the solid-state Li/Cu@Sn|PVDF–HFP–5 wt% SiO_2 |LFP battery, and the capacity does not decay after 500 cycles at 1 C. Conclusively, this study provides a strategy for preparing 3D current collectors for high-energy-density LMBs, which may be used to fabricate other metal current collectors or metal batteries.

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Conflict of interest The authors declare that they have no conflict of interest.

Supplementary information Experimental details and supporting data are available in the online version of the paper.

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三维亲锂Cu@Sn纳米锥集流体用于无枝晶锂金属负极

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摘要 锂在集流体上的不均匀沉积将导致严重的枝晶生长和体积膨胀等问题, 传统的商业化泡沫铜集流体由于具有较大的体积和质量会降低电池的能量密度. 本文通过简单的电沉积方法制备了体积小、重量轻, 具有亲锂性的3D Cu@Sn纳米锥集流体. 从成核与沉积的角度出发, 纳米锥结构与亲锂的锡纳米颗粒的协同作用促进了锂的均匀沉积, 可有效地抑制锂枝晶的生长. 组装的半电池在1 mA cm⁻²下经过100次循环后, 库仑效率高达97.6%, 锂对称电池在1 mA cm⁻²下可以稳定循环600 h. 将沉积金属锂后的Cu@Sn/Li复合负极与LiFePO₄组装的液态全电池在1 C倍率下, 550个循环之后, 容量保持率为95.1%. 此外, Cu@Sn纳米锥集流体在固态电池Li/Cu@Sn|PVDF–HFP–5 wt% SiO₂|LFP中也表现出优异的电化学性能, 在1 C倍率下, 500个循环之后, 放电容量未发生衰减.