Artificial cathode solid electrolyte interphase to endow highly stable lithium storage of FeF₂ nanocrystals

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ABSTRACT Iron difluoride (FeF₂) is considered a high-capacity cathode material for lithium-ion batteries. However, its specific capacity and stability are limited by the poor electrochemical kinetics of conversion reactions. Herein, the conversion reaction is confined in a localized nanosized space by encapsulating FeF₂ nanoparticles in polymer gelatin. The FeF₂ nanocrystal-coated polyvinylidene fluoride-based layer (defined as FeF₂@100%G-40%P) was synthesized by glucose-assisted *in-situ* gelatinization to construct an artificial cathode solid electrolyte interphase *via* a solvothermal process. Thanks to the improved kinetics of the localized conversion reaction, the obtained FeF₂@100%G-40%P electrodes show good cyclic stability (313 mA h g⁻¹ after 150 cycles at 100 mA g⁻¹, corresponding to a retention of 80%) and a high rate performance (186.6 mA h g⁻¹ at 500 mA g⁻¹).

Keywords: FeF₂ nanocrystals, artificial PVDF-based CEI layer, cyclic stability, lithium-ion batteries

INTRODUCTION

Lithium-ion batteries (LIBs) are considered vital energy storage devices [1,2]. To meet the demand for high energy density, researchers have developed high-capacity cathode materials for LIBs, such as chalcogenides (S/Li₂S [3], Se/Li₂Se [4]), and fluorides (MF_x [5–10]). Iron difluoride (FeF₂) as a conversion-type cathode material has been extensively studied due to its high theoretical capacity of 571 mA h g⁻¹ and energy density of 1519 Wh kg⁻¹ for LIBs. However, the agglomeration of conversion products of active materials, the electrochemical sintering, and severe voltage hysteresis phenomenon commonly occur in conversion-type lithium storage materials, leading to the loss of specific capacities. Furthermore, the large bandgap of FeF₂ induced by the high ionic state of metal–F bonds results in its electrical insulator nature, which is harmful to lithium storage performance [11]. Various novel strategies have been attempted to improve the electron conductivity and stabilize the interfacial layer of active materials and electrolytes. Recently, the method of encapsulating the transitional MF_x with a carbonous shell (TMF@C) has been shown to be an effective strategy to achieve high electrochemical performance of fluoride [12,13]. For instance, FeF₂@C nanorods fabricated *via* a one-pot thermal reaction of ferrocene and polyvinylidene fluoride (PVDF) can significantly improve their cycling stability. However, its exces-

sively thick encapsulation layer limits the diffusion of lithium ions into the electrode [13,14]. Additionally, the decomposition of MF_x at high temperatures is a massive challenge for the synthesis of TMF@C [15]. Another method is to stabilize the interface with Li salt composites [16,17]. Recently, Pasta's group [18] revealed that an *in situ*-formed cathode solid electrolyte interphase (CEI) layer could significantly improve the cycling stability of FeF₂ nanorods. However, the quality of the CEI layer strongly depends on the composition of the electrolyte and the working conditions. The reported high-quality CEI layer can only be generated in the ionic liquid-based electrolytes at 50°C and it fails in commonly used LiPF₆/ethylene carbonate:dimethyl carbonate electrolytes. Fluoroethylene carbonate (FEC) is usually used as an additive in the electrolyte of rechargeable batteries to form a high-quality CEI for the cathode. Wu *et al.* [19] reported an electrolyte with a high content of FEC, which formed a robust fluorinated CEI to passivate the surface of the Na_{2/3}Ni_{1/3}-Mn_{2/3}O₂ cathode, ensuring long cycling stability. However, fabricating an elastic, thin, and homogeneous CEI layer on active materials *via* a gentle synthesis method is still challenging [20]. PVDF with high thermal stability and sufficient strength can effectively prevent slumping and cracking of active particles and is an ideal material for the binder and porous separator of liquid LIBs.

Herein, a PVDF-based artificial CEI layer prepared through *in-situ* gelatinization was coated on FeF₂ nanocrystals (defined as FeF₂@100%G-40%P) *via* a one-step solvothermal process. Glucose was used as the reducing agent to regulate the structure of FeF₂ in this reaction. Thanks to the improved kinetics of the localized conversion reaction in Scheme 1, the FeF₂@100%G-40%P electrodes exhibited a robust cycling performance of 313 mA h g⁻¹ after 150 cycles at 100 mA g⁻¹, corresponding to a retention of 80% and a high rate capacity (186.59 mA h g⁻¹ at 500 mA g⁻¹).

EXPERIMENTAL SECTION

Synthesis of FeF₂ and PVDF-FeF₂ composites

FeF₃·3H₂O (180 mg) and D(+)-glucose (180 mg, 100 wt% FeF₃·3H₂O) were milled to obtain a homogeneous reactant mixture and stirred vigorously for 1 h in butyl-alcohol (75 mL) at room temperature. The suspension was transferred into a Teflon-lined 100-mL stainless-steel autoclave reactor. After being subsequently sealed, the reactor was heated at 180°C for

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Scheme 1 The artificial CEI layer restricts the agglomeration of the conversion products, the rupture, and the shedding of the active materials.

24 h in an oven. The product was cooled to room temperature and washed thrice with absolute ethanol. The products were labeled $\text{FeF}_2@x\%\text{G}$ depending on the ratio of glucose (10%, 20%, 60%, 100%, 150%, and 200%). $\text{FeF}_3 \cdot 3\text{H}_2\text{O}$ (180 mg), *D*(+)-glucose (180 mg), and PVDF (y wt% of $\text{FeF}_3 \cdot 3\text{H}_2\text{O}$) were milled to a homogeneous reactant mixture and reacted under the same conditions as $\text{FeF}_2@x\%\text{G}$. The products were named $\text{FeF}_2@100\%\text{G}-y\%\text{P}$ (10%, 20%, 40% and 60%).

Characterization

The morphology and structure of the samples were characterized on a D/max 2550 VL/PC diffractometer (Rigaku, Japan) with $\text{Cu K}\alpha$ radiation (40 kV, 30 mA, $\lambda = 1.5418 \text{ \AA}$) and JEOL JEM-2100F. Raman spectra were measured by Raman microscopy at 532 nm. The pore size distribution and specific surface areas were calculated by an NOVA 2200e analyzer. X-ray photoelectron spectroscopy (XPS) was conducted with a Versa Probe PHI-5000 multi-X-ray photoelectron spectrometer (ULVAC-PHI Inc., Japan), and the calibration was based on the C 1s (binding energy -284.8 eV) peak.

Electrochemical measurements

Active materials (70 wt%), carbon black (15 wt%, Super-P, Timcal), and binder (15 wt% PVDF) were mixed in *N*-methylpyrrolidinone (NMP) to form a slurry that was coated on aluminum foil and then dried for 8 h at 80°C . The typical mass loading of the active materials was about 1 mg cm^{-2} . Half-cells were assembled using CR2016 coin cells for LIBs in an argon-filled glove box ($\text{O}_2 \leq 0.1 \text{ ppm}$, $\text{H}_2\text{O} \leq 0.01 \text{ ppm}$), 1 mol L^{-1} lithium trifluorosulfonamide salt (LiTFSI) in a mixture of FEC/ethyl methyl carbonate (3:7 by vol%) as the electrolyte, and polypropylene membrane (UBE Industries Ltd.) as the separator. Galvanostatic discharge/charge measurements were performed on a LAND-CT2001A system in the voltage range of 1.0–4.0 V (vs. Li^+/Li) at room temperature. Cyclic voltammetry (CV) was performed using an electrochemical workstation (ZAHNER Zennium) at 0.3 mV s^{-1} .

RESULTS AND DISCUSSION

Structure and morphology

The crystal structures of $\text{FeF}_2@x\%\text{G}$ were characterized by X-ray diffraction (XRD) and scanning electron microscopy (SEM), as shown in Fig. 1a–f. The products obtained by the solvothermal reaction have good crystallinity. It can be seen from XRD that when the glucose content is 10%, the sample shows a crystallization peak of $\text{FeF}_3 \cdot 0.33\text{H}_2\text{O}$ (JCPDS No. 076-1262), and when the glucose content is higher than 20%, the product is totally converted to rutile structure FeF_2 (JCPDS No. 045-1062), and no peak of $\text{FeF}_3 \cdot 0.33\text{H}_2\text{O}$ can be observed. Previous reports indicated that $\text{FeF}_3 \cdot 3\text{H}_2\text{O}$ was dehydrated to form small nanoparticles at 180°C , followed by the formation of $\text{FeF}_3 \cdot 0.33\text{H}_2\text{O}$ nanorods [21–23]. The presence of a small amount of glucose partially reduced Fe^{3+} to Fe^{2+} (Fig. 1f). Lack of passivation caused oriented growth of FeF_2 and formation of cluster-like structures during cooling [24]. An increase in glucose feed ratio further reduced the Fe^{3+} , and excess glucose as a surfactant guided the formation and aggregation of the particles, and the FeF_2 was completely passivated into nanoparticles. These nanoparticles aggregated in different ways to form two morphologies. The overall morphologies of FeF_2 obtained with PVDF are nearly the same as those obtained at 20% and 100%, indicating that PVDF has nearly no effect on the growth mechanism of FeF_2 (Fig. S1). This indicates that the self-assembly results of the material should be attributed to glucose instead of PVDF.

Transmission electron microscopy (TEM) was used to analyze the micromorphology of the composite material. As shown in Fig. 2, the material is made up of small particles with a size close to 10 nm. The presence or absence of PVDF makes an essential difference on the micro profiles. The PVDF makes the material smoother, and regular layered structures appear in high-resolution TEM (HRTEM). HRTEM shows that the interplanar spacing of the compound is 0.27 nm (corresponding to the (101) plane of FeF_2). From the HRTEM image (Fig. 2f), the PVDF layer of the $\text{FeF}_2@100\%\text{G}-40\%\text{P}$ sample can be seen to be uni-

Figure 1 (a) SEM image of FeF₃·3H₂O; (b–d) SEM images of FeF₂@10%G, FeF₂@20%G and FeF₂@40%G, respectively; (e) XRD spectra; (f) product simulation diagram with increasing amount of glucose.

Figure 2 (a, b) TEM, (c) HRTEM images of FeF₂@100%G; (d, e) TEM, and (f) HRTEM images of FeF₂@100%G-40%P.

formly coated on the FeF₂ nanoparticles, and the thickness of the PVDF layer is about 3 nm. Fig. S2 shows the scanning transmission electron microscopy-energy dispersive X-ray spectroscopy (STEM-EDX) elemental mapping of Fe, F, and C.

XPS and Raman spectroscopy were used to study the effect of PVDF on the chemical composition of the FeF₂@10%G,

FeF₂@100%G, and FeF₂@100%G-40%P electrodes. Fig. 3a–d show the Fe 2p, O 1s, F 1s, and C 1s peaks of the four electrode materials. For Fe 2p XPS, 2p_{3/2} at ~712 eV and 2p_{1/2} at ~725 eV components of Fe²⁺ were observed. The difference is that FeF₂@10%G has a certain shift. In PVDF-containing electrodes, the core level spectra of the surface F 1s show the two strongest

Figure 3 (a) Fe 2p, (b) F 1s, (c) O 1s and (d) C 1s XPS spectra; (e) FTIR spectra of PVDF, FeF₂@100%G and FeF₂@100%G-40%P; and (f) Raman spectra of FeF₂@x%G and FeF₂@x%G-y%P.

peaks at ~685 and ~687 eV, which are attributed to the FeF₂ and C-F bonds. The C 1s core level spectra show rich chemical properties, and its spectrum can be resolved into several components corresponding to different chemical bonds. The peak at ~284 to ~285 eV is attributed to the C-H bond or the C-C bond. The strong peak at 286.2 eV comes from the C-O bond, probably from the glucose in the raw material. Compared with materials without PVDF, the peak at 290.6 eV should be derived from CF₂. Four groups of PVDF were planned in different proportions, which were 10%, 20%, 40%, and 60%, and the excess PVDF formed a tough film during the deposition and cooling of the bottom of the reactor when the feed was higher than 60%. According to the inductively coupled plasma optical emission spectrometry results, the active material FeF₂ added to the 40% composite material was the lowest (69.5 wt%), and the content of FeF₂ in the 20% and 60% composite material was above 80 wt%. The highest FeF₂ content could reach 93.5%. The chemical state of PVDF in the composites was characterized by

Fourier transform infrared spectrometry (FTIR) (Fig. 3e). One can see that the PVDF infrared characteristic peak after the reaction has the opposite trend to that of the initial PVDF. Specifically, the vibration absorption peak of O-C-O corresponding to 1404 cm⁻¹ and the stretching vibration absorption peak of CF₂ corresponding to 1180 cm⁻¹ were enhanced [25,26]. The vibrational absorption peaks of the crystalline phases at 976, 795, 763, and 713 cm⁻¹ disappeared, while the characteristic absorption peaks of the amorphous phases at 880 and 840 cm⁻¹ increased [27]. Moreover, the Raman spectrum of the composite material shows two bands near 1360 cm⁻¹ (D band) and 1600 cm⁻¹ (G band) (Fig. 3f). The strength of the D-band increased with the increase in the amount of PVDF added, indicating that more defects or voids were formed in the material. Initial PVDF, FeF₂@100%G and FeF₂@100%G-40%P containing the same mass of PVDF were dispersed/dissolved in *N*-methyl pyrrolidone (NMP) solvent. After 72 h of stirring, the pure NMP and NMP solutions with initial PVDF, FeF₂@100%G

and $\text{FeF}_2@100\%\text{G}-40\%\text{P}$ had visible viscosity differences (Fig. S3). The surface areas of $\text{FeF}_2@100\%\text{G}$ and $\text{FeF}_2@100\%\text{G}-40\%\text{P}$ were studied by the nitrogen isothermal adsorption technique (Fig. S4), and the results showed that the surface areas of $\text{FeF}_2@100\%\text{G}-40\%\text{P}$ and $\text{FeF}_2@100\%\text{G}$ were 59.643 and $92.689\text{ m}^2\text{ g}^{-1}$, respectively, which may be due to the PVDF buffer layer increasing the particle size and filling the gaps between the particles. The organic structure created by PVDF may improve the ion conductivity of the electrode and facilitate the migration of Li^+ .

Electrochemical performances of the electrodes

The electrochemical performances of the electrodes were evaluated by galvanostatic charge/discharge measurements. The initial lithiation/delithiation profiles of the $\text{FeF}_2@100\%\text{G}$, $\text{FeF}_2@100\%\text{G}-10\%\text{P}$, $\text{FeF}_2@100\%\text{G}-20\%\text{P}$, $\text{FeF}_2@100\%\text{G}-40\%\text{P}$, and $\text{FeF}_2@100\%\text{G}-60\%\text{P}$ electrodes at 100 mA g^{-1} are shown in Fig. S5. The initial coulombic efficiencies (ICEs) of the $\text{FeF}_2@100\%\text{G}$, $\text{FeF}_2@100\%\text{G}-10\%\text{P}$, $\text{FeF}_2@100\%\text{G}-20\%\text{P}$, $\text{FeF}_2@100\%\text{G}-40\%\text{P}$, and $\text{FeF}_2@100\%\text{G}-60\%\text{P}$ electrodes were 44.1%, 51.6%, 53.6%, 55.0%, and 42.3%, respectively. The $\text{FeF}_2@100\%\text{G}-40\%\text{P}$ electrode showed the highest ICE of 55.0% due to its thin and uniform PVDF layer reducing side reactions during the process of lithiation.

The specific discharge capacities of the FeF_2 with different glucose feed ratios at 100 mA g^{-1} shown in (Fig. 4a) indicate that $\text{FeF}_2@100\%\text{G}$ has a discharge capacity of $463.38\text{ mA h g}^{-1}$ and

maintains $121.26\text{ mA h g}^{-1}$ after 100 cycles, while $\text{FeF}_2@60\%\text{G}$ and $\text{FeF}_2@150\%\text{G}$ present 45.22 and 96.16 mA h g^{-1} , respectively. In addition, a cliff decay occurred in cluster-like $\text{FeF}_2@20\%\text{G}$ within the first 20 cycles, which had the highest capacity of $669.87\text{ mA h g}^{-1}$ at the first discharge cycle and a lower capacity of 27.79 mA h g^{-1} at the 20th cycle, indicating that not all special structures could increase the electrochemical performance of the positive electrode; however, the capacity was greatly reduced due to the collapse of the structure during the charge/discharge cycle. The galvanostatic charge/discharge measurements of the electrode materials with different ratios of PVDF at 100 mA g^{-1} at 25°C are listed in Fig. 4b. The results show that insufficient PVDF caused a decaying performance, such as $\text{FeF}_2@20\%\text{G}$. The gaps between the nanoparticles are unevenly filled with viscous PVDF, which may induce the squeezing and shedding of the active particles during the volume changes caused by the charge/discharge process, and lead to poor electronic conductivity and low capacity retention, along with larger volume changes and greater polarization with higher currents, so the specific capacity is reduced to below 10 mA h g^{-1} after 20 cycles at 100 mA g^{-1} in the rate test.

$\text{FeF}_2@100\%\text{G}-40\%\text{P}$ with the best performance has a specific capacity of $314.42\text{ mA h g}^{-1}$ after 100 cycles with a starting capacity of $404.26\text{ mA h g}^{-1}$ (based on the active material, FeF_2), which is significantly higher than the capacity of other proportions of PVDF active materials. A high coincidence rate curve and the efficiency close to 100% are observed from the charge/

Figure 4 Gravimetric specific discharge capacities and coulombic efficiency of (a) $\text{FeF}_2@x\%\text{G}$ and (b) $\text{FeF}_2@x\%\text{G}-y\%\text{P}$. The electrode was charged/discharged between 1.0 and 4.0 V (vs. Li^+/Li) at 100 mA g^{-1} ; (c) CV of $\text{FeF}_2@100\%\text{G}$ and $\text{FeF}_2@100\%\text{G}-40\%\text{P}$ electrodes from 1 to 4 V (rate cycling of the $\text{FeF}_2@100\%\text{G}-40\%\text{P}$ electrodes inside); (d) galvanostatic charge/discharge profiles of the $\text{FeF}_2@x\%\text{G}-y\%\text{P}$ electrodes.

Figure 5 (a, b) TEM and (c) HRTEM of $\text{FeF}_2@100\%\text{G}-40\%\text{P}$ after 200 cycles.

discharge curve of $\text{FeF}_2@100\%\text{G}-40\%\text{P}$ in the second to fifth cycles, as shown in Fig. 4c. In addition, when the amount of PVDF was increased to 60%, the poor stability exhibited by the $\text{FeF}_2@100\%\text{G}-60\%\text{P}$ electrode and the charge-discharge specific capacity was lower than those of $\text{FeF}_2@100\%\text{G}-60\%\text{P}$, which was attributed to excess PVDF deposition. The oligomeric microspheres hinder the migration of Li^+ and significantly reduce its cycling performance.

Two lithiated regions during discharge represent the intercalation reaction and the conversion reaction. The first region should form $\text{Li}_x\text{Fe}_{2-x}\text{F}_2$ from the open-circuit voltage to 2.0 V with the insertion of Li ions into Fe^{3+} impurities from some Fe^{2+} oxidized by exposure to air. Due to the functionalization of the particle surface and the protection of the PVDF buffer layer, the first region is nearly vertical and shows a discharge capacity of 20 mA h g^{-1} , indicating that there was no significant lithium intercalation reaction. The second lithiated region is a redox platform below 2 V, ascribed to the conversion reaction of FeF_2 to $\alpha\text{-Fe}$. Combining the CVs of $\text{FeF}_2@100\%\text{G}$ and $\text{FeF}_2@100\%\text{G}-40\%\text{P}$, it can be observed that the presence of PVDF increases the voltage of the electrode material and that the increase of the discharge current guides the sharpness of the discharge peak. During the delithiation process (charging), $\text{FeF}_2@100\%\text{G}-40\%\text{P}$ showed a single wide peak at 2.9 V vs. Li/Li^+ and contributed almost half of the capacitance. In contrast, the charging curve of $\text{FeF}_2@100\%\text{G}$ fluctuates greatly, and the charging current shows a substantial rising trend before the peak of 2.75 V.

To highlight the ability of $\text{FeF}_2@100\%\text{G}-40\%\text{P}$ to improve the electrochemical performance of FeF_2 electrode materials, charge and discharge tests were performed at different rates (Fig. 4d). The $\text{FeF}_2@100\%\text{G}-40\%\text{P}$ electrode exhibited specific discharge capacities of 228.17 and $186.59 \text{ mA h g}^{-1}$ at currents of 300 and 500 mA g^{-1} , reaching 56% and 46% of 100 mA g^{-1} , respectively. After rate cycling, the electrode could still recover a discharge capacity of 375 mA h g^{-1} under a current of 50 mA g^{-1} . The high stability of the electrode material under a large current could be confirmed by the prominent discharge peak in the CV diagram. $\text{FeF}_2@100\%\text{G}-20\%\text{P}$ and $\text{FeF}_2@100\%\text{G}-60\%\text{P}$ are relatively weak, showing only 84 and $144.95 \text{ mA h g}^{-1}$ at a current of 500 mA g^{-1} . Returning to 50 mA g^{-1} after 30 cycles, the $\text{FeF}_2@100\%\text{G}-20\%\text{P}$ and $\text{FeF}_2@100\%\text{G}-60\%\text{P}$ electrodes decreased rapidly to 125 and 200 mA h g^{-1} , respectively. The $\text{FeF}_2@100\%\text{G}-40\%\text{P}$ electrode has higher capacity, rate performance, and cycle stability, indicating that equivalent PVDF can improve the stability of the electrode and help it charge/discharge quickly.

Electrochemical impedance spectroscopy (EIS) was used to

investigate the electrochemical performance of various electrodes after 25 and 50 cycles in the delithiation state. As shown in Fig. S6, the $\text{FeF}_2@100\%\text{G}$ and $\text{FeF}_2@100\%\text{G}-10\%\text{P}$ electrodes showed strong internal resistance after 50 cycles compared with the first cycle. At the same time, the impedance spectra of the $\text{FeF}_2@100\%\text{G}-20\%\text{P}$, $\text{FeF}_2@100\%\text{G}-40\%\text{P}$, and $\text{FeF}_2@100\%\text{G}-60\%\text{P}$ electrodes remained essentially unchanged after 50 cycles. In particular, the $\text{FeF}_2@100\%\text{G}-40\%\text{P}$ electrode showed the smallest semicircle compared with the other electrodes after 50 cycles, implying the smallest charge transfer resistance and fastest ion diffusivity.

TEM was performed on the positive electrode material after 200 cycles. The cathode material after cycling retains its morphology before cycling and it has a smaller particle size. In HRTEM scanning, there are three kinds of crystal lattices with obvious size differences: 0.38 nm (FeF_3), 0.27 nm (FeF_2), and 0.20 nm (Fe) (Fig. 5). The lattice of 0.20 nm was concentrated inside the particle, mainly due to the uneven aggregation of Fe nanoparticles and LiF during the discharge process. The 0.38 nm crystal lattice appears on the surface of the particles, which is due to the pseudocapacitive effect caused by the increase in Fe valence due to overcharge/discharge. Together, these factors cause a small amount of battery capacity loss during cycling.

Based on the above analyses, $\text{FeF}_2@100\%\text{G}-40\%\text{P}$ has better cycle stability and rate performance, which can be attributed to the structural protection of PVDF gelation. The open, plastic thin walls attenuate the volume expansion and collapse of the material and allow the material to have better cycle stability than $\text{FeF}_2@100\%\text{G}$. In particular, the introduction of PVDF forms a buffer layer on the surface of the particles, effectively restraining the volume expansion and improving organic electrolyte wettability. After 200 cycles, the high adhesion ability enables excellent electrical contact between the particles and conductive agent, inhibiting particle agglomeration. The small size of FeF_2 particles can shorten the electron transmission distance, thereby achieving high capacity utilization and small voltage hysteresis.

CONCLUSIONS

In summary, a special material that can be used for LIB cathodes was prepared using glucose reduction by a solvothermal method. Electrochemical testing showed that high-rate performance and cyclic capacity could be implemented by introducing a suitable amount of PVDF, which caused a stable structure to buffer volume change and supported a thin and conformal layer. The $\text{FeF}_2@100\%\text{G}-40\%\text{P}$ electrode exhibited a robust cycling performance of 313 mA h g^{-1} after 150 cycles at 100 mA g^{-1} and a

high rate capacity of 186.59 mA h g⁻¹ at 500 mA g⁻¹. The superior performance of the cathodes provides an effective way to prepare materials with high energy density for LIBs.

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Supplementary information Supporting data are available in the online version of the paper.

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人工正极固体电解质膜赋予 FeF_2 纳米晶正极材料良好的储锂循环稳定性

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摘要 氟化亚铁被认为是锂离子电池的高容量正极材料. 然而, 由于转换反应的电化学动力学不佳, 它们的比容量和稳定性受到很大限制. 如果将转换反应限域在纳米空间中, 可有效避免由于活性物质的长大而导致的失活. 本文中, 我们通过葡萄糖还原和聚偏氟乙烯原位包覆的方法, 在 FeF_2 纳米晶体表面构建了一层聚偏氟乙烯基人工正极固体电解质膜(CEI)(材料定义为 $\text{FeF}_2@100\%\text{G}-40\%\text{P}$). 由于纳米限域空间改善了转化反应的动力学, 抑制了纳米晶长大, 所获得的 $\text{FeF}_2@100\%\text{G}-40\%\text{P}$ 电极显示出良好的循环稳定性(在 100 mA g^{-1} 的电流密度下, 循环150次比容量为 313 mA h g^{-1} , 容量保持率为80%)和高倍率性能(在 500 mA g^{-1} 的电流密度下, 比容量为 186.6 mA h g^{-1}).