



CHALMERS
UNIVERSITY OF TECHNOLOGY

Monodispersed FeS₂ Electrocatalyst Anchored to Nitrogen-Doped Carbon Host for Lithium–Sulfur Batteries

Downloaded from: <https://research.chalmers.se>, 2026-04-07 07:22 UTC

Citation for the original published paper (version of record):

Sun, W., Liu, S., Li, Y. et al (2022). Monodispersed FeS₂ Electrocatalyst Anchored to Nitrogen-Doped Carbon Host for Lithium–Sulfur Batteries. *Advanced Functional Materials*, 32(43).
<http://dx.doi.org/10.1002/adfm.202205471>

N.B. When citing this work, cite the original published paper.

Monodispersed FeS₂ Electrocatalyst Anchored to Nitrogen-Doped Carbon Host for Lithium–Sulfur Batteries

Weiwei Sun,* Shuangke Liu, Yujie Li, Danqin Wang, Qingpeng Guo, Xiaobin Hong, Kai Xie, Zhongyun Ma, Chunman Zheng,* and Shizhao Xiong*

Despite their high theoretical energy density, lithium–sulfur (Li–S) batteries are hindered by practical challenges including sluggish conversion kinetics and shuttle effect of polysulfides. Here, a nitrogen-doped continuous porous carbon (CPC) host anchoring monodispersed sub-10 nm FeS₂ nanoclusters (CPC@FeS₂) is reported as an efficient catalytic matrix for sulfur cathode. This host shows strong adsorption of polysulfides, promising the inhibition of polysulfide shuttle and the promoted initial stage of catalytic conversion process. Moreover, fast lithium ion (Li-ion) diffusion and accelerated solid–solid conversion kinetics of Li₂S₂ to Li₂S on CPC@FeS₂ host guarantee boosted electrochemical kinetics for conversion process of sulfur species in Li–S cell, which gives a high utilization of sulfur under practical conditions of high loading and low electrolyte/sulfur (E/S) ratio. Therefore, the sulfur cathode (S/CPC@FeS₂) delivers a high specific capacity of 1459 mAh g⁻¹ at 0.1 C, a stable cycling over 900 cycles with ultralow fading rate of 0.043% per cycle, and an enhanced rate capability compared with cathode only using carbon host. Further demonstration of this cathode in Li–S pouch cell shows a practical energy density of 372 Wh kg⁻¹ with a sulfur loading of 7.1 mg cm⁻² and an E/S ratio of 4 μL mg⁻¹.

electric vehicles and portable electronics devices.^[1–4] Lithium–sulfur (Li–S) batteries are considered as one of the most promising candidates among next-generation battery technologies due to their low cost, high theoretical specific capacity (1675 mAh g⁻¹), and energy density (2600 Wh kg⁻¹).^[5–7] Despite of these advantages, Li–S batteries are yet to achieve the sufficient properties for commercialization because of low utilization of active material and limited long-term cycling ability, which are primarily attributed to the poor conductivity of elemental sulfur/lithium sulfides, shuttle effect of lithium polysulfides (LiPSs), and sluggish kinetics for the conversion of sulfur species.^[8–11]

To address these issues, tremendous effort has been devoted to the fabrication of effective hosts for sulfur cathode. Conductive carbon-based matrixes with high specific surface area and porosity are

widely studied as host materials, which can provide accommodation for active mass sulfur, buffering space for the volume change, and efficient network for electron transfer in electrodes.^[12–14] Despite great progress achieved, nonpolar carbonaceous host materials possess poor chemical affinity to polar LiPSs, resulting in the active diffusion of LiPSs away from cathode since they are highly soluble in the ether-based liquid electrolyte. To suppress the shuttle effect that is based on the diffusion of LiPSs, polar transition metal materials such as oxides,^[15,16] chalcogenides,^[17–20] nitrides,^[21,22] phosphides,^[23,24] and carbides^[25,26] have been introduced into carbon host and they are demonstrated to present strong chemical interactions toward LiPSs. However, the limited adsorption sites of the carbon host will be easily occupied to reach a saturated state due to the sluggish conversion kinetics, leading to the constant diffusion of LiPSs into electrolyte, especially for the sulfur cathodes with high loading active mass.^[27–29] During the discharge process of Li–S battery, the rate-determining step for the conversion of sulfur species is the solid–solid conversion process from Li₂S₂ to Li₂S which contributes almost half theoretical capacity and the high activation energy of this process restricts the full conversion, leading to low utilization of sulfur as well as limited capacity obtained.^[30–32] Therefore, design of electrocatalyst for accelerating the reaction kinetics of sulfur is a promising strategy for developing high-energy-density Li–S batteries.


1. Introduction

Increasing demand for advanced energy storage technologies has been created owing to the rapid development of

W. Sun, S. Liu, Y. Li, D. Wang, Q. Guo, X. Hong, K. Xie, C. Zheng
College of Aerospace Science and Engineering
National University of Defense Technology
Changsha 410073, China
E-mail: wwsun@nudt.edu.cn; zhengchunman@nudt.edu.cn

Z. Ma
Department of Chemistry
Key Laboratory of Environmentally Friendly Chemistry and Applications
of Ministry of Education
Xiangtan University
Xiangtan 411105, China

S. Xiong
Department of Physics
Chalmers University of Technology
Göteborg SE 412 96, Sweden
E-mail: shizhao.xiong@chalmers.se

 The ORCID identification number(s) for the author(s) of this article can be found under <https://doi.org/10.1002/adfm.202205471>.

© 2022 The Authors. Advanced Functional Materials published by Wiley-VCH GmbH. This is an open access article under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

DOI: 10.1002/adfm.202205471

Recently, iron (Fe)-based chalcogenides have been demonstrated to present efficient catalytic effect for hydrogen evolution reaction, water splitting, and oxygen reduction reaction, showing advantages of high conductivity, good economy, and chemical stability.^[33,34] For application in Li–S batteries, Fe-based sulfides have been employed as electrocatalyst for the conversion of sulfur species.^[35,36] However, the energy density and cycling life of the Li–S batteries are still hindered by the low surface area, low porosity, and poor microstructure of the electrocatalysts. Therefore, design and fabrication of Fe-based sulfides as efficient electrocatalyst of sulfur species is the key for improving the utilization of sulfur in high-energy-density Li–S batteries. To build practical Li–S batteries, pouch cell is the important prototype to evaluate the key performance of Li–S cells including energy density and areal capacity under the realistic conditions for commercialization, like high loading of sulfur (>5 mg cm⁻²), low ratio of electrolyte/sulfur (E/S) (<5 μL mg⁻¹), and limited excess Li anode.^[37–39] Nevertheless, electrocatalysts like Fe-based sulfides are barely reported in Li–S pouch cells under practical condition since the large-scale synthesis of these catalysts is still challenging.

In this work, we report a cost-effective nitrogen-doped continuous porous carbon (CPC) host anchoring sub-10 nm FeS₂ nanoclusters as an efficient electrocatalyst (CPC@FeS₂), which is aiming to accelerate the conversion kinetics of Li₂S₂ to Li₂S for high energy density Li–S batteries. Our results show that the synergistic engineering of CPC@FeS₂ host delivers large interior space for high loading of sulfur and the dramatic volume change during conversion process of sulfur species. Moreover, the host provides abundant catalytic active sites for adsorption of polysulfides and conversion of the solid intermediate products like Li₂S₂. Therefore, the sluggish kinetic for solid–solid

conversion of Li₂S₂ to Li₂S is significantly promoted, contributing to the suppression of shuttle effect and high utilization of active mass. The sulfur cathode based on the host (S/CPC@FeS₂) presents a high specific capacity, improved rate capability and long-term cycling stability with 0.043% capacity fading rate per cycle for 900 cycles. Li–S pouch cell with this cathode shows a competitive energy density of 338 Wh kg⁻¹ under conditions of high areal capacity of 8.5 mAh cm⁻², high sulfur loading of 8.4 mg cm⁻², and a very low E/S ratio of 3.5 μL mg⁻¹. Furthermore, optimization of sulfur loading and E/S ratio can lift the energy density of Li–S pouch cell to a record high level as 372 Wh kg⁻¹. Our results shed light on the design of advanced carbon host possessing efficient electrocatalysts and conductive network for high performance sulfur cathode as well as practical Li–S battery.

2. Results and Discussion

The synthesis procedure of S/CPC@FeS₂ composite is illustrated in **Figure 1a**. The nitrogen-doped CPC host was first synthesized through a carbonization process followed by acid etching, where sodium citrate was employed as self-template as well as carbon precursor and melamine was used as source of nitrogen functional group.^[40] The nitrogen group on the surface of the CPC host endows the electronegative property and the adsorption energy (E_{ads}) for Fe³⁺ with N atom is –4.87 eV, which is much higher than that with C atom (–2.61 eV), as seen in **Figure 1b**. Consequently, the Fe³⁺ ions highly prefer to adsorb on the nitrogen-doped active site of CPC when it is dispersed in FeCl₃ aqueous solution. A further sulfidation step uniformly creates sub-10 nm FeS₂ nanoclusters on the CPC host, named

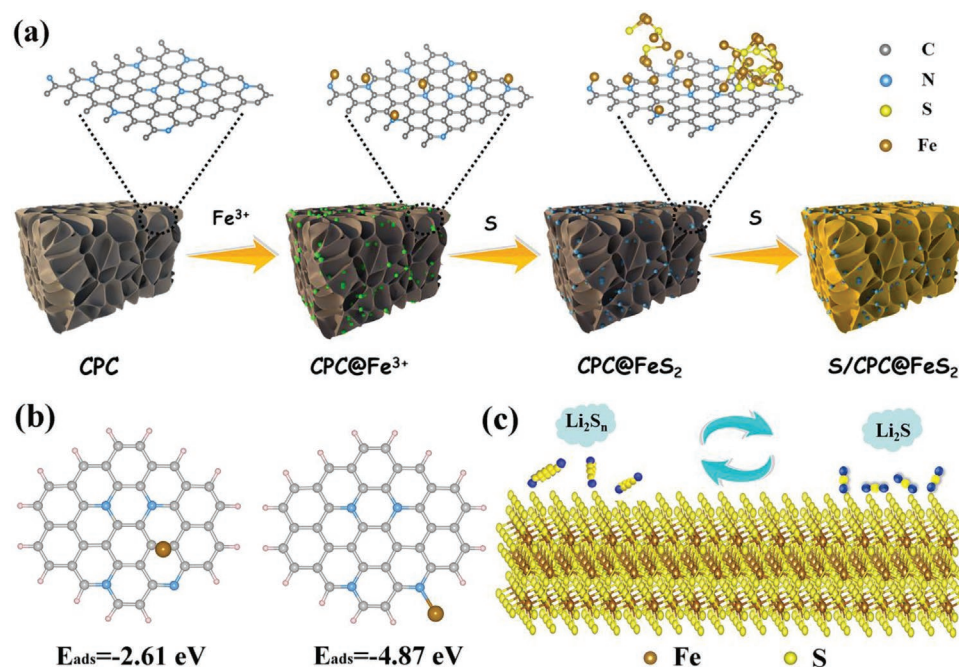


Figure 1. Schematic illustration of synthesis of cathode host and the electrocatalytic process. a) Synthesis process of S/CPC@FeS₂ composite. b) Optimized adsorption configurations and the corresponding binding energy of Fe³⁺ with C atom and N atom, respectively. c) Electrocatalytic sites of FeS₂ for sulfur species.

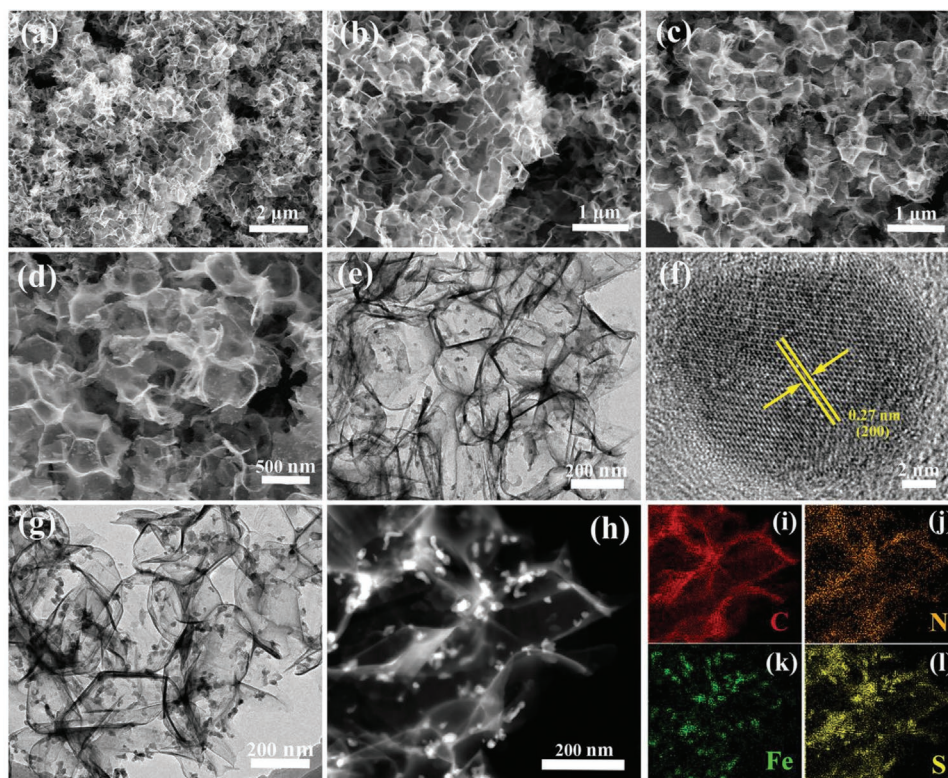


Figure 2. Morphology of CPC@FeS₂ host and sulfur cathode. SEM images of a,b) CPC and c,d) CPC@FeS₂. e,f) High-resolution transmission electron microscopy (HRTEM) images of CPC@FeS₂ host. g–l) TEM images and the corresponding EDS elemental distribution maps of S/CPC@FeS₂ cathode.

as CPC@FeS₂. The FeS₂ nanoparticle is expected to show a crystal structure of cubic symmetry (Figure S1, Supporting Information) and the CPC@FeS₂ host is promising to deliver abundant catalytic sites for the conversion of sulfur species (Figure 1c). Lastly, the sulfur cathode based on this carbon host (S/CPC@FeS₂) was obtained by the melting-diffusion process.

To obtain the microstructures of the CPC@FeS₂ host and as-prepared sulfur cathode, scanning electron microscopy (SEM) and high-resolution transmission electron microscope (TEM) are conducted. SEM images of CPC host (Figure 2a,b) show the nanoarchitecture with continuous porous network constructed by massive carbon nanosheets. This structure is further demonstrated by TEM images in Figure S2a,b of the Supporting Information and the carbon nanosheets presents a thickness of ≈7 nm. The integrated porous structure fabricated by the ultrathin carbon nanosheets allows the high electronic/ionic conductivity in the network and enough internal space for volume change as well as high loading of active sulfur. The FeS₂ nanoparticles were uniformly anchored to the nitrogen-doped CPC host by electrostatic adsorption of Fe³⁺ to nitrogen atoms and the host maintains the nanostructure during the growth process of FeS₂, as shown in Figure 2c–e. The energy dispersive X-ray spectroscopy (EDS) of CPC@FeS₂ host indicates the coexistence of C, N, Fe, and S elements, as seen in Figure S2e of the Supporting Information. Interestingly, if only sodium citrate is used as carbon precursor without melamine (precursor for nitrogen doping), the SEM images of the final product show that almost no FeS₂ nanoparticle is loaded on the carbon nanosheet (Figure S3, Supporting Information). Moreover, the

typical diffraction peaks of FeS₂ cannot be discerned in X-ray diffraction (XRD) pattern of the product prepared without melamine, see Figure S4 of the Supporting Information. This proves that the monodispersed FeS₂ nanoclusters are enabled by the doping nitrogen atoms. The nanostructure of FeS₂ is further revealed by TEM images in Figure 2f, showing a nanocrystalline with a diameter of ≈5 nm and an interplanar spacing of 0.27 nm which is corresponding to the (200) crystal planes.^[35] The sulfur cathode based on the carbon host (S/CPC@FeS₂) shows similar morphology (Figure 2g; Figure S2c,d, Supporting Information) to that before the infiltration of active mass sulfur, indicating a robust structure of the host. Furthermore, the EDS mapping of S/CPC@FeS₂ cathode (Figure 2h–l) reveals the uniform distribution of C, N, Fe, and S elements in the composite.

To understand the interaction between sulfur and carbon host, chemical and structural analysis of the host and S/CPC@FeS₂ cathode are carried out. The negative zeta potential CPC powder in deionized water (Figure 3a) suggests that the doping nitrogen atoms promise adsorption sites for Fe³⁺ and thus homogeneous distribution of formed FeS₂. X-ray photoelectron spectroscopy (XPS) for CPC host in Figure S5 of the Supporting Information shows the presence of C, N, and O elements. The corresponding high-resolution C 1s spectrum (Figure 3b) is fitted with three peaks at 288.3, 285.5, and 284.4 eV, which are in agreement with C=O, C–N, and C–C, respectively.^[41] The C–N functional groups show the strong bonding between the doped nitrogen atoms and carbon host. Fitting of N 1s spectrum of CPC (Figure 3c) reveals four nitrogen compounds, pyridinic N at 398.2 eV, pyrrolic N at 400.0 eV, graphitic N at 400.5 eV, and

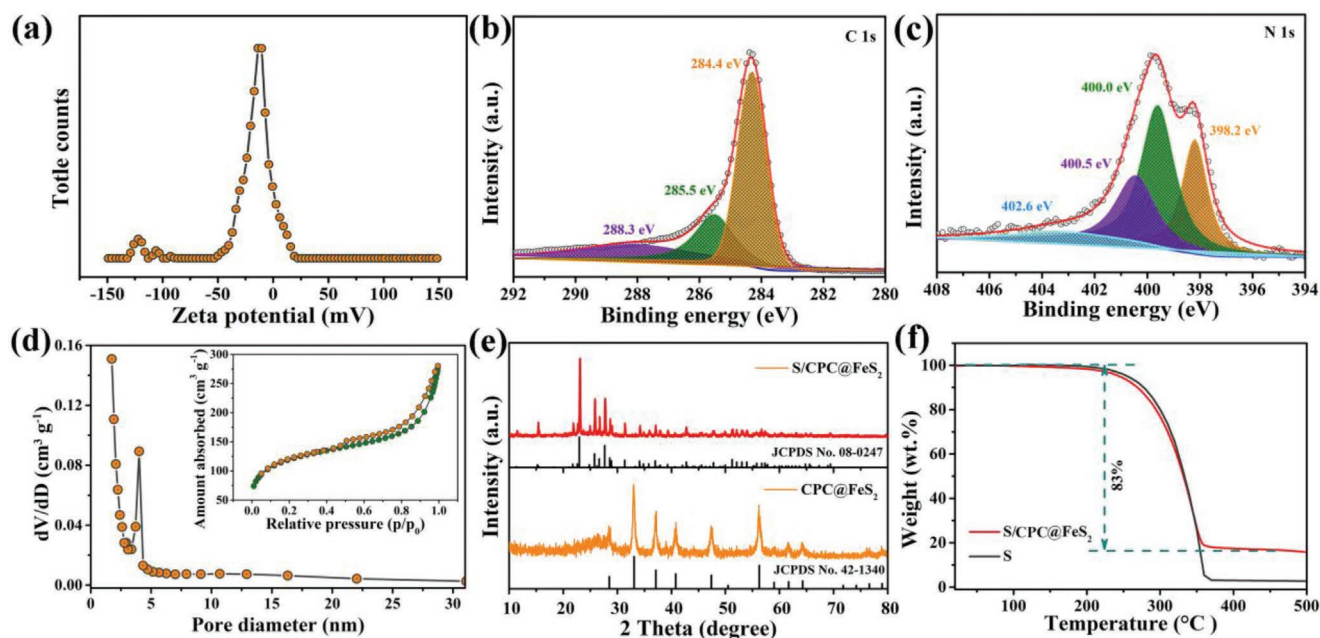


Figure 3. Chemical and structural analysis of carbon host and sulfur cathode. a) Zeta potential of CPC powder in deionized water. b,c) High-resolution XPS spectra of C1s and N1s for CPC. d) Pore size distribution and corresponding nitrogen adsorption/desorption isotherms (the inset) of CPC. e) XRD patterns of CPC@FeS₂ host and S/CPC@FeS₂ cathode. f) TGA curves of sulfur and S/CPC@FeS₂ cathode.

oxidic N at 402.6 eV, which allow high electrical conductivity of the host and massive adsorption sites for LiPSs.^[42] Figure S6 of the Supporting Information shows the Raman spectra of pure CPC and CPC@FeS₂, which contain main peaks corresponding to vibration modes for graphitic edge defects (D 1350 cm⁻¹) and ideal graphite (G 1580 cm⁻¹). It can be seen that the I_G/I_D of CPC is determined as 1.11, slightly lower than that of CPC@FeS₂ composite (1.19), implying a higher graphitization of the obtained CPC@FeS₂. Abundant mesopores of 4 nm in diameter and high specific surface area of 405 m² g⁻¹ are obtained for the CPC host by Brunauer–Emmett–Teller (BET) method (see Figure 3d), showing the great capacity for sulfur loading, volume change, and abundant catalytic sites on the host surface. After infiltrated with sulfur, the specific surface area of the S/CPC@FeS₂ is measured to be 10 m² g⁻¹ (Figure S7, Supporting Information). The characteristic peaks in XRD patterns (Figure 3e) of CPC@FeS₂ host are attributed to crystalline cubic FeS₂ (JCPDS No. 42–1340).^[43] Moreover, the typical diffraction peaks of sulfur in the S/CPC@FeS₂ cathode reveal the successful loading of sulfur into the host by the melting-diffusion method. Thermal gravimetric analysis (TGA) was conducted to identify the content of various species in the carbon host as well as in the as-prepared sulfur cathode. The TGA curves in Figure 3f and Figure S8 (Supporting Information) show that the content of FeS₂ in the CPC@FeS₂ host is about 25 wt% and the mass fraction of sulfur in the S/CPC@FeS₂ cathode is 83%.

To corroborate the interaction between the carbon host and LiPSs, which are the intermediate products during the operation of Li–S battery, the adsorption experiments were performed by mixing CPC@FeS₂ or CPC powder into solution of Li₂S₆. Optical visualization of the experiments is shown in Figure 4a and the solution with CPC@FeS₂ powder was obviously decolorized after shelving while the one with CPC is still

in dark tawny color, suggesting much more adsorption of LiPSs in CPC@FeS₂ host compared to that with CPC host.^[21] The CPC@FeS₂ host adsorbed with LiPSs is analyzed by high-resolution XPS and the fitted spectra of Fe 2p are presented in Figure 4b. After the adsorption of LiPSs, the Fe 2p peaks for CPC@FeS₂ host show a shift to lower binding energy, which reveals the chemical affinity between them. Furthermore, a new peak around 720 eV shows up and this is attributed to new FeS_x species formed by the chemical reaction between FeS₂ and LiPSs, which is an additional proof for the strong interactions of polar FeS₂ with LiPSs.^[41,44] The effective chemisorption of LiPSs on the CPC@FeS₂ host is further demonstrated by the positive shift of S 2p peaks and the new peak 168 eV (Figure 4c), which is corresponding to the oxidation of sulfur species on the host.^[45]

The intrinsic interaction between FeS₂ and sulfur species was simulated at atomic level by theoretical density functional theory (DFT) to elaborate the adsorption mechanism.^[46–50] Figure 4e–g shows the rendering for optimized geometric configurations of typical soluble sulfur species on (200) surface of FeS₂ and the corresponding binding energies (E_b) are presented in Figure 4d. The calculated E_b for Li₂S₄, Li₂S₆, and Li₂S₈ are 1.10, 1.36, and 1.73 eV, respectively. The results obtained on the FeS₂ surface are much higher than that on N-doped carbon as previously reported.^[51] Our simulation results are consistent with the adsorption experiment, demonstrating the strong binding strength of LiPSs to CPC@FeS₂ host. It is generally accepted that the adsorption is the first step for catalytic conversion process and the strong adsorption of sulfur species in CPC@FeS₂ host shows a great promise for the efficiency of FeS₂ electrocatalyst.

Apart from the chemical adsorption, there are other rate controlling steps for the conversion of sulfur species in Li–S

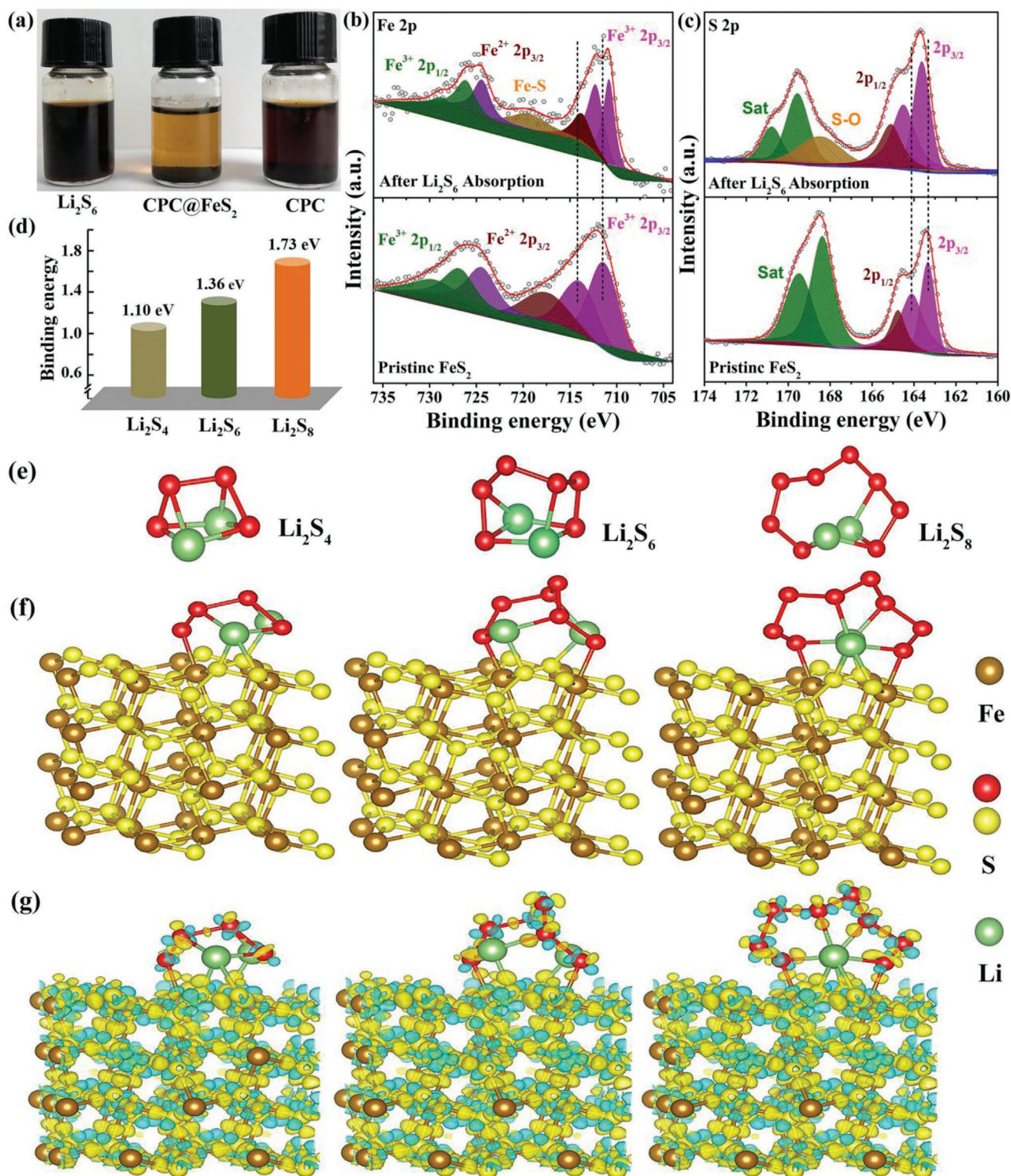


Figure 4. Interaction between polysulfides and CPC@FeS_2 host. a) Visualization experiments for the adsorption of polysulfides by CPC host and CPC@FeS_2 host. b,c) High-resolution XPS spectra at Fe 2p (b) and S 2p (c) regions for pristine CPC@FeS_2 and $\text{CPC@FeS}_2\text{-Li}_2\text{S}_6$, respectively. d) Simulation of binding energy and e–g) optimized adsorption configurations and electronic density differences for Li_2S_4 , Li_2S_6 , and Li_2S_8 on FeS_2 (200) surface, respectively.

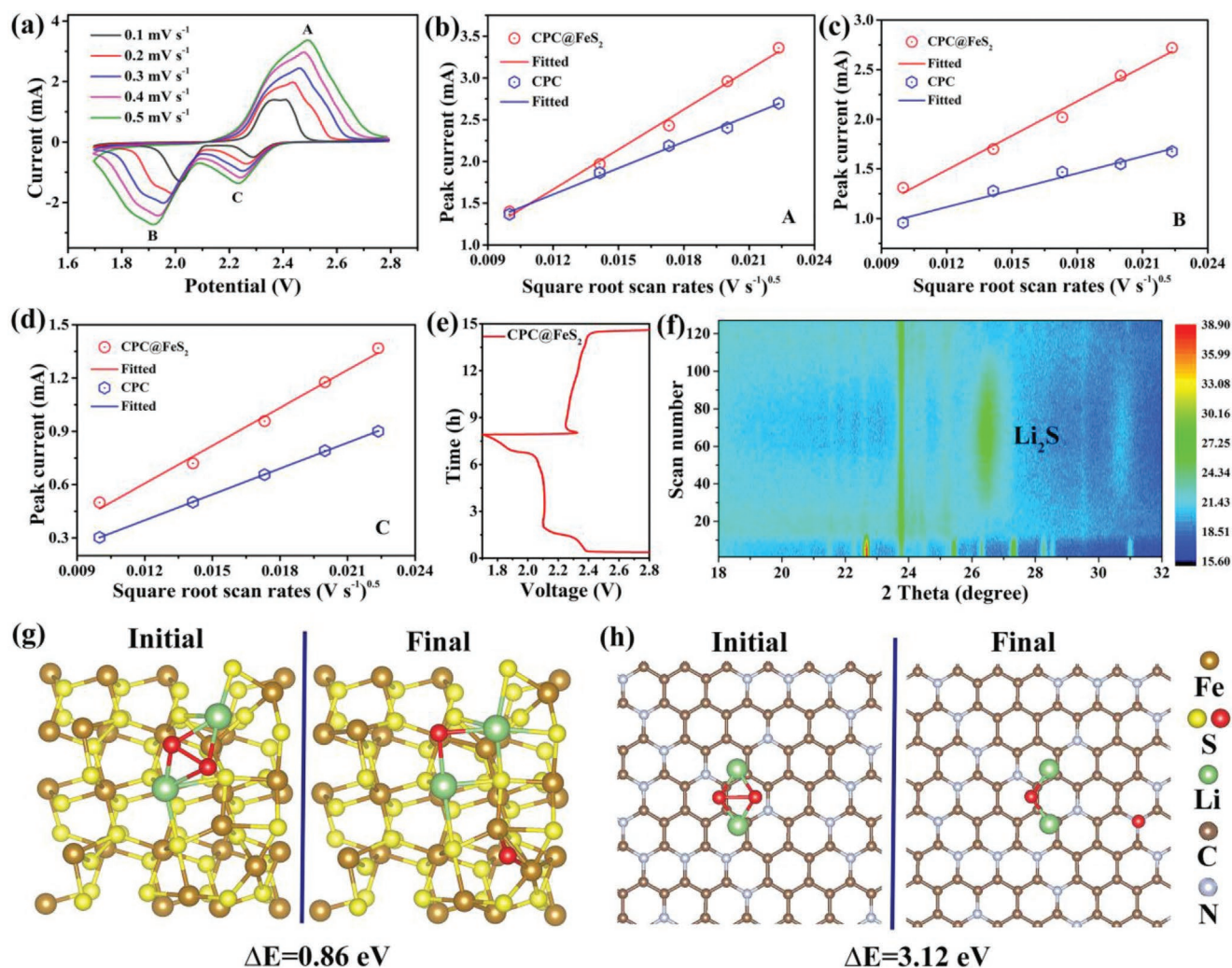


Figure 5. Electrochemical kinetic of sulfur species on CPC@FeS₂ host. a) CV curves of S/CPC@FeS₂ cathode under different scanning rates from 0.1 to 0.5 mV s⁻¹. b–d) Peak current for the cathodic and anodic peaks A, B, and C for S/CPC@FeS₂ and S/CPC cathodes versus the square root of scanning rate. e, f) In situ XRD contour plots (f) of S/CPC@FeS₂ cathode and the corresponding discharge/charge curve (e). g, h) Dissociation energy (ΔE) of Li₂S₂ to form Li₂S on the surface of FeS₂ (g) and N-doped carbon (h).

battery, which is including the adsorption of LiPSs to the surface of carbon host, diffusion of Li-ion and the dissociation from Li₂S₂ to Li₂S, as shown in Figure S9 of the Supporting Information. To investigate the role of Li-ion diffusivity on the kinetic of conversion reaction for sulfur species, cyclic voltammetry (CV) under various scanning rates (0.1–0.5 mV s⁻¹) were carried out for S/CPC@FeS₂ cathode and S/CPC cathode, which is prepared with CPC host. The correlation between peak currents for anodic and cathodic reactions (Figure 5a; Figure S10, Supporting Information) with the square root of scanning rates is described by the Randles–Sevcik equation^[42]

$$I_p = 2.69 \times 10^5 \cdot n^{1.5} \cdot S \cdot D_{Li^+}^{0.5} \cdot C_{Li^+} \cdot \nu^{0.5} \quad (1)$$

where I_p is the value of peak current, n is the number of transferred electrons for the reaction, S is the area of electrode, D_{Li^+} is the diffusion coefficient for Li⁺, C_{Li^+} is the concentration of Li⁺ in electrolyte, and ν represents the scanning rate. Therefore,

the slope of $I_p/\nu^{0.5}$ is used to estimate the diffusion coefficient of Li⁺. The fitted slopes for the three reactions in Figure 5b–d shows that the value for S/CPC@FeS₂ cathode are greater than that for S/CPC cathode, indicating higher diffusion coefficients of Li⁺ in the S/CPC@FeS₂ cathode, which is beneficial to the conversion reaction kinetics of sulfur species.

For the conversion reactions in Li–S battery, the solid–solid transformation between Li₂S₂ and Li₂S is considered the main rate controlling step and this process contributes half the theoretical capacity.^[31] Here, in situ XRD was conducted to track the catalytic conversion process of Li₂S on the CPC@FeS₂ host. The in situ cell made of S/CPC@FeS₂ cathode was cycling at a rate of 0.1 C and the XRD patterns in a contour plot as well as corresponding voltage profile are shown in Figure 5e, f and Figure S11 (Supporting Information). During the discharge process, the characteristic peaks for sulfur are obviously detected at the initial stage and its intensity gradually reduces with the increasing depth of discharge. At the same time, the

characteristic peak for Li_2S at $\approx 26.5^\circ$ shows up.^[17] At the end of discharge process, the peaks for sulfur disappear while the highest intensity of the peak for Li_2S is obtained, indicating an efficient conversion of sulfur species to Li_2S on the CPC@ FeS_2 host. During the charge process, the intensity of the peak for Li_2S shows a gradual reduction, suggesting a high reversibility for the conversion of Li_2S to Li_2S_2 or polysulfides in the S/CPC@ FeS_2 cathode. The catalytic mechanism of FeS_2 for the conversion from Li_2S_2 to Li_2S is further demonstrated by the DFT calculations. The optimized atomic structure of Li_2S_2 is simulated for its adsorption on surface of the FeS_2 and N-doped carbon, see Figure 5g,h. The binding energy for FeS_2 and Li_2S_2 is 4.38 and it is 0.61 eV for the adsorption of Li_2S_2 on N-doped carbon surface, revealing a good chemical affinity of Li_2S_2 to FeS_2 . Moreover, the dissociation energy (ΔE) of Li_2S_2 on FeS_2 surface is calculated as 0.86 eV, which is much smaller than that on the surface of N-doped carbon (3.12 eV). This suggests that the energy barrier for the conversion from Li_2S_2 to Li_2S on the surface of FeS_2 is significantly lowered and the efficient catalytic activity of FeS_2 will promote the utilization of active mass for Li-S battery.

The catalytic activity of the CPC@ FeS_2 host is further examined in Li-S cells by CV and electrochemical impedance spectroscopy (EIS). The CV profiles (Figure 6a) of S/CPC@ FeS_2 and

S/CPC cathodes shows two typical cathodic peaks which are corresponding to reduction of sulfur to LiPSs and the following reduction to $\text{Li}_2\text{S}_2/\text{Li}_2\text{S}$, and one anodic peak, which is assigned to the reverse oxidation reactions.^[52] The smaller potential difference for the anodic peak and the second cathodic peak and higher peak current indicates that the conversion reaction kinetics for S/CPC@ FeS_2 cathode is accelerated compared with that in S/CPC cathode.^[53] The CV profile of pure CPC@ FeS_2 is also obtained with the range from 1.7 to 2.8 V, which is shown in Figure S12 of the Supporting Information. It can be seen that no redox reactions of CPC@ FeS_2 exist under this conditions. The EIS spectra (Figure 6b) show that the diameter of semi-circle corresponding to the charge transfer resistance is smaller for S/CPC@ FeS_2 cathode, revealing a faster charge transfer in this cathode. The voltage profiles (Figure 6c) for various sulfur cathodes in coin cells show the impact of FeS_2 electrocatalyst on the charge/discharge process of Li-S battery. For the charge process, a lower potential of 1.87 V at initial stage and a smaller potential barrier of 2.24 V are obtained in S/CPC@ FeS_2 cathode, suggesting that there are more reductive sulfur species produced in the cathode and the conversion kinetic for Li_2S is boosted.^[17] Moreover, the lower polarization between charge and discharge further demonstrates the function of CPC@ FeS_2 host as effective electrocatalyst.

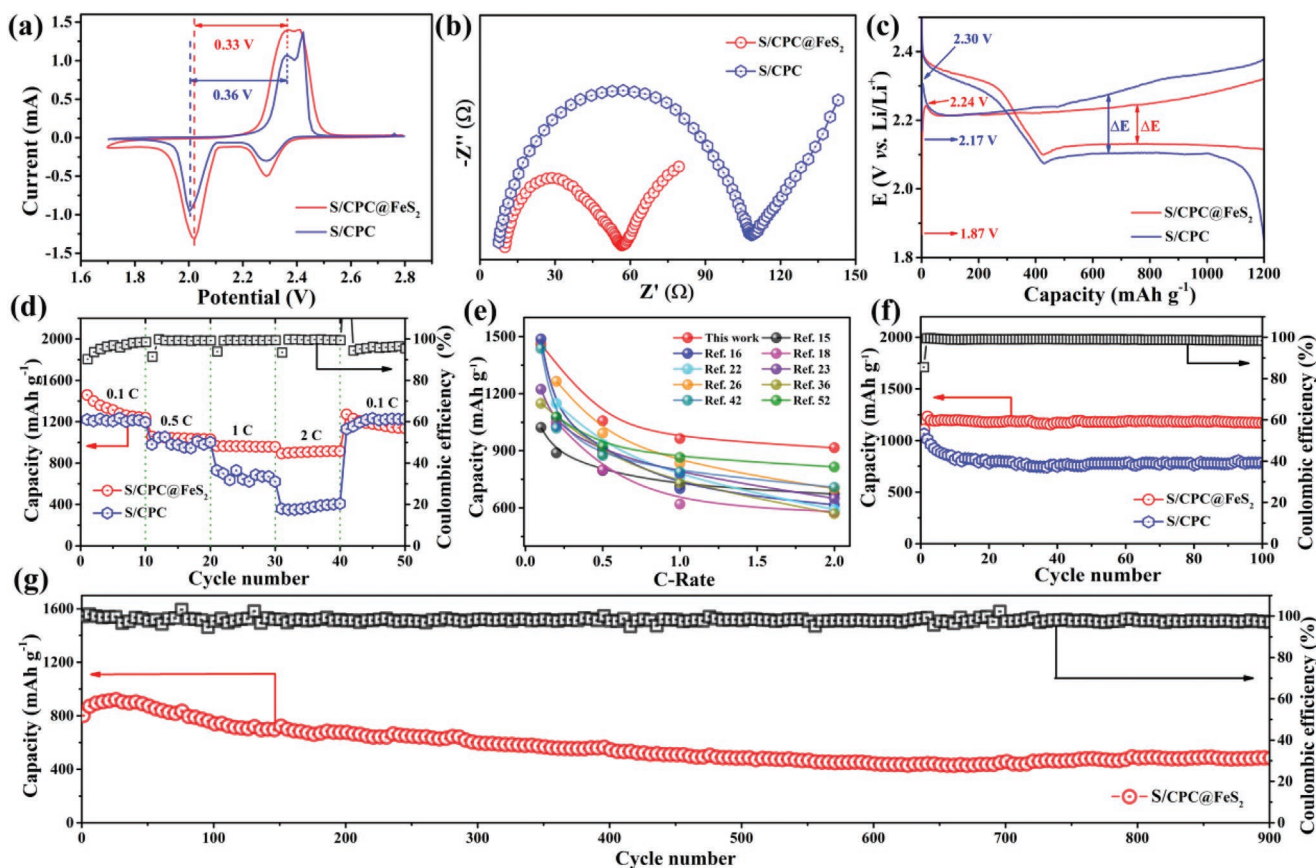


Figure 6. Electrochemical performance of Li-S coin cells. a) Comparison of potential difference from CV profiles at 0.1 mV s^{-1} . b) EIS plots of different cathodes before cycling. c,d) voltage profile at 0.1 C (c) and rate capabilities (d) of Li-S cells using S/CPC@ FeS_2 and S/CPC cathodes. e) Comparisons of rate performance between this work with reported prevailing sulfur hosts. f) Cycling performance of Li-S cells at 0.4 C with S/CPC@ FeS_2 and S/CPC cathodes. g) Cycling stability and Coulombic efficiency of S/CPC@ FeS_2 cathode at 1.5 C .

The electrochemical performance of S/CPC@FeS₂ cathode is evaluated by galvanostatic cycling under various rates within a voltage range of 1.7–2.8 V, as shown in Figure 6d. The S/CPC@FeS₂ cathode shows a highest capacity of 1459 mAh g⁻¹ at 0.1 C and a capacity of 916 mAh g⁻¹ under high rate of 2 C, which are outstanding among the results reported for host materials in sulfur cathodes (Figure 6e). By contrast, the S/CPC cathode without FeS₂ electrocatalyst only shows a capacity of 407 mAh g⁻¹ at 2 C. The cycling performance of S/CPC@FeS₂ and S/CPC cathodes is examined at 0.4 C for 100 cycles, see Figure 6f. The specific capacity for S/CPC@FeS₂ cathode is 1232 mAh g⁻¹ at initial cycles and it maintains 1171 mAh g⁻¹ after cycling, showing 95% of the capacity retention with a high Coulombic efficiency of 99% during the whole cycling. However, the S/CPC cathode only maintains 74% of the initial capacity. To demonstrate the cycling stability of S/CPC@FeS₂

cathode under practical conditions, a long-term cycling of S/CPC@FeS₂ cathode is performed under 1.5 C for 900 cycles, as seen in Figure 6g. A capacity retention of 60% is obtained and the fading rate for each cycle is as low as 0.043%, showing a competitive cycling performance compared with previous reports of sulfur cathodes listed in Table S1 of the Supporting Information.

To demonstrate the capability of large-scale preparation of this host material and its application, S/CPC@FeS₂ cathode is used to assemble Li–S pouch cells (Figure 7a). The Li–S pouch cell is made of S/CPC@FeS₂ cathode, Li foil as well as Celgard separator, and it is assembled by coiling procedure and finally packed into a laminate bag. To achieve high energy density for the cell, a high sulfur loading (≥ 7 mg cm⁻²) in S/CPC@FeS₂ cathode and a lean electrolyte (E/S ratio ≤ 4 μ L mg⁻¹) are applied. The Li–S pouch cell is tested at 0.1 C and the voltage profiles

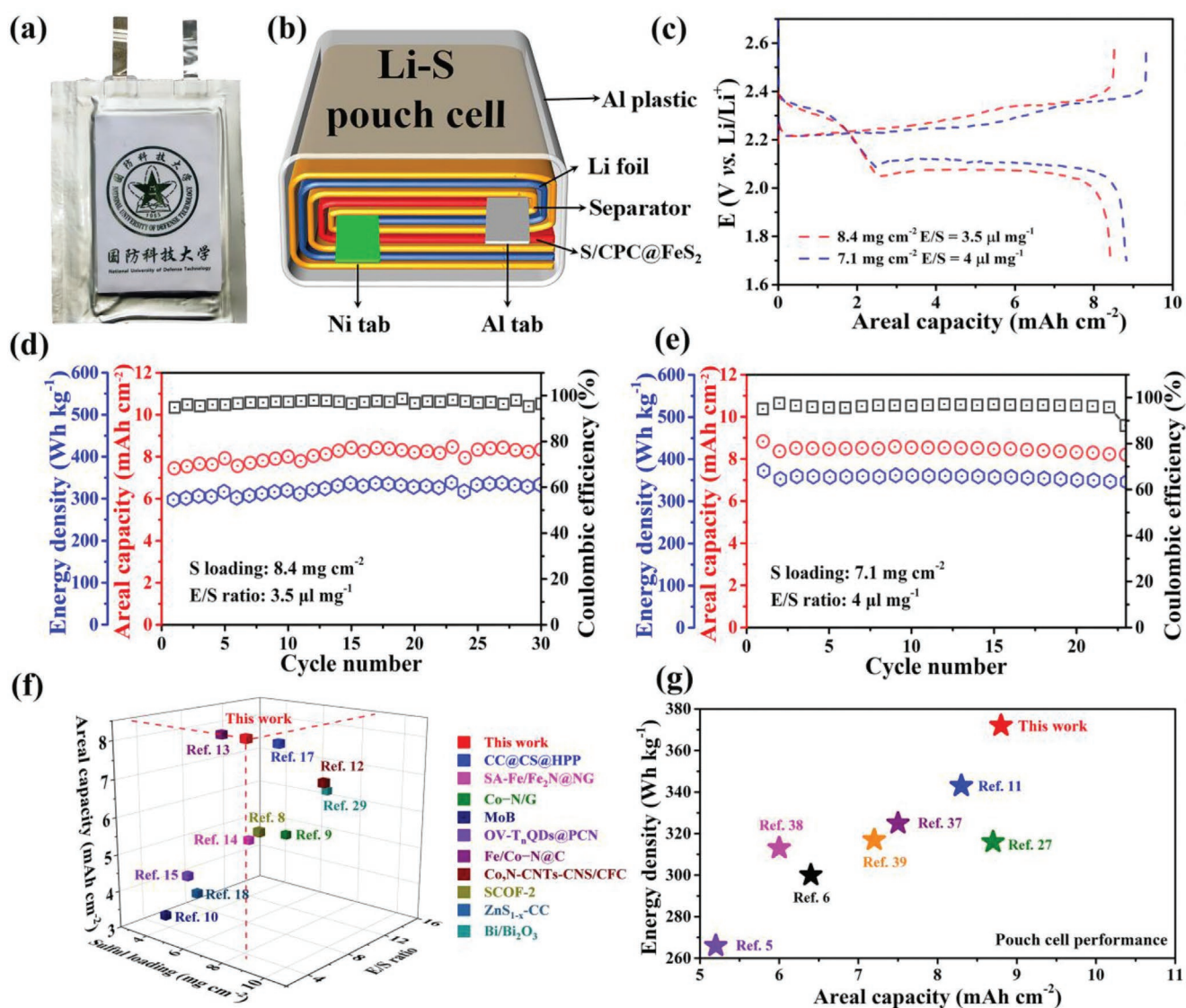


Figure 7. Electrochemical performance of Li–S pouch cells with high loading S/CPC@FeS₂ cathode. a) Photograph and b) schematic diagram of Li–S pouch cells. c) Discharge–charge profiles of Li–S pouch cell with different sulfur loading and E/S ratio at 0.1 C. d,e) Cycling stability of Li–S pouch cells at 0.1 C. f) Comparison of key parameters (E/S ratio, sulfur loading, and areal capacity) of pouch cells in this work with reported data. g) Comparison of areal density and energy density with previously reported Li–S pouch cells.

are displayed in Figure 7c, showing two typical plateaus for discharge process as in coin cells. As shown in Figure 7d, the pouch cell delivers a high areal capacity is 8.5 mAh cm⁻² from the sulfur loading of 8.4 mg cm⁻² in the cathode under an ultralow E/S ratio of 3.5 μL mg⁻¹ and this gives a capacity of 1008 mAh g⁻¹ for active mass and a high energy density of 338 Wh kg⁻¹ at cell level including entire weight of sulfur cathode, current collector, electrolyte, separator, and Li anode. Moreover, this pouch cell shows a retention energy density of 333 Wh kg⁻¹ after 30 cycles. To achieve higher energy density for Li–S pouch cell, the sulfur loading and E/S ratio are furthered optimized to obtain a high specific capacity of 1239 mAh g⁻¹ for active mass, which is a significant improvement in pouch cells. The cell with lower sulfur loading of 7.1 mg cm⁻² and higher E/S ratio of 4 μL mg⁻¹ delivers a similar areal capacity of 8.8 mAh cm⁻² and much higher energy density of 372 Wh kg⁻¹, see Figure 7e. This suggests that specific capacity for active mass is another important aspect to be considered for high energy density Li–S battery besides the sulfur loading and E/S ratio. By contrast, the Li–S cell using S/CPC cathode only has a specific capacity of 958 mAh g⁻¹ and energy density of 288 Wh kg⁻¹ under similar conditions (sulfur loading of 7.2 mg cm⁻² and E/S ratio of 4 μL mg⁻¹, Figure S13, Supporting Information). The advanced performance of Li–S cell with S/CPC@FeS₂ cathode is also compared with previous reports and shows a great achievement (Figure 7f,g). To show the potential application of Li–S pouch cell, an array of light-emitting diodes with a pattern is powered by a cell, see Figure S14 of the Supporting Information.

3. Conclusions

In this work, we designed and synthesized a CPC@FeS₂ host in which the nitrogen-doped continuous porous carbon is anchored with the catalytic FeS₂ nanoclusters, and this host shows a great promise to build high performance sulfur cathode for Li–S battery. The CPC@FeS₂ host has a highly conductive network for electrons, a robust porous architecture, and active sites of electrocatalyst, providing a multifunctional carrier for the conversion of sulfur species. The host material shows a strong adsorption to LiPSs, enhanced diffusivity of Li-ion and the accelerated kinetics for the sluggish solid–solid transformation of Li₂S₂ to Li₂S, which are beneficial to high utilization of active mass and rate capability of sulfur cathode. Therefore, the S/CPC@FeS₂ sulfur cathode delivers a high specific capacity of 1459 mAh g⁻¹ and a stable cycling over 900 cycles. The Li–S pouch cell with this sulfur cathode has a high energy density 372 Wh kg⁻¹ under practical conditions with a sulfur loading of 7.1 mg cm⁻² and an E/S ratio of 4 μL mg⁻¹. Our work not only provides a strategy to design carbon host material for efficient conversion of sulfur species, but also shows the capability for large-scale application of this material in high energy Li–S battery.

4. Experimental Section

Synthesis of CPC@FeS₂ Host: Nitrogen-doped CPC was synthesized by the modified procedure reported in previous literature.^[40] Briefly,

1 g melamine and 10 g sodium citrate were mixed through grinding in a mortar and subsequently the mixture was annealed at 700 °C for 2 h under argon atmosphere. The product after annealing was dispersed in a solution of 4 m HCl and stirred for 24 h. The CPC was obtained after filtrating and drying at 80 °C for 12 h. To prepare CPC@FeS₂ host, 0.2 g CPC powder was dispersed in 50 mL of 0.1 m FeCl₃ solution and subsequently stirred at 45 °C for 6 h to obtain fully adsorption of Fe³⁺. The product was collected by filtering and drying, then mixed with sublimed sulfur and calcined at 350 °C for 3 h under argon atmosphere.

Synthesis of S/CPC and S/CPC@FeS₂ Composite: Both S/CPC and S/CPC@FeS₂ composites were prepared by the classical melting diffusion method. The host material (CPC or CPC@FeS₂) was mixed with sulfur by a weight ratio of 1:5 in 10 mL of CS₂ and then stirred for 5 h to evaporate the solvent. The mixture was further heated at 155 °C for 12 h to obtain the cathode material.

Characterization: XRD measurements for identifying crystalline structure and composition of the materials were conducted on Rigaku TTR-3 system with a Cu Kα radiation. Morphology of the carbon samples was obtained by SEM (Hitachi S-4800). TEM analysis was performed with a Tecnai F20 TEM system equipped with the EDS. Zeta potential of CPC powder was measured by a zeta sizer system (Malvern Instruments). The chemical analysis of sample surface was conducted on a PHI-1600 X-ray photoelectron spectroscope (XPS). TGA (TGA-600) of samples was performed at a heating rate of 10 °C min⁻¹ in argon atmosphere. The distribution of pores and specific surface area of CPC host were measured by BET method. In situ XRD measurement on Li–S cell was performed on a Bruker X-ray diffractometer and the cell was operated between 1.7 and 2.8 V at a rate of 0.1 C rate.

Adsorption Measurement for LiPSs: The solution of Li₂S₆ was prepared by mixing sulfur and Li₂S with a molar ratio of 1:5 in the mixed solvent (1,3-dioxolane and 1,2-dimethoxyethane, v/v = 1:1) for 12 h stirring. Next, 5 mg of CPC or CPC@FeS₂ powder was added into the Li₂S₆ solution for fully adsorption of LiPSs and the CPC@FeS₂/Li₂S₆ powder was obtained after filtrating and drying for XPS measurement.

Electrochemical Tests: The electrochemical performance of the S/CPC and S/CPC@FeS₂ cathodes was first evaluated in standard CR2032 coin cell. The coin cell was assembled with sulfur cathode, electrolyte (1 m lithium bis(trifluoromethanesulfonyl)imide and 0.2 m lithium nitrate in the mixed solvent of 1,3-dioxolane and 1,2-dimethoxymethane with volume ratio of 1:1), and Li foil in an argon atmosphere glovebox. The average loading of sulfur in cathodes for coin cells was ≈1.6 mg cm⁻², and the E/S ratio was set as 15 μL mg⁻¹. The discharge/charge cycling of coin cells was performed on LAND system under the range of 1.7 and 2.8 V. The currents for rate capability were calculated with 1 C = 1675 mA g⁻¹. The CV and EIS measurements were conducted on a Princeton VersaSTAT potentiostat system. For fabrication of pouch cell, the sulfur cathode was prepared by dispersing S/CPC@FeS₂ composite, Super P and LA133 binder in deionized water with a mass fraction of 87:7:6. Subsequently, the slurry was casted on Al foil and dried under vacuum at 60 °C for 12 h. The pouch cell was assembled by coiling sulfur cathode, Celgard 2400, and lithium foil with a sandwich structure. High sulfur loading and low E/S ratio was applied for pouch cells, see Section 2.

Calculation of Energy Density for Pouch Cell: The energy density of Li–S pouch cell (E_{cell}) was estimated at device level by the equation

$$E_{\text{cell}} = CV / M = M_s C_s V / (M_{\text{Al}} + M_{\text{cat}} + M_{\text{ele}} + M_{\text{Li}} + M_{\text{sep}}) \quad (2)$$

where C is the capacity (mAh), V is the average voltage of cell (V), M_s is the areal loading of sulfur in cathode (mg cm⁻²), C_s is the specific capacity of active mass (mAh g⁻¹), M_{Al} is the areal mass of Al foil (mg cm⁻²), M_{cat} is the areal mass of the whole cathode (mg cm⁻²), M_{ele} is the areal mass of electrolyte (mg cm⁻²), M_{Li} is the areal mass of Li foil (mg cm⁻²), and M_{sep} is the areal mass of separator (mg cm⁻²).

Theoretical Calculations: DFT computation in this work was carried out using the Vienna ab initio simulation package. Projector augmented wave potentials^[46–48] and Perdew–Burke–Ernzerhof functional within the generalized gradient approximation^[49] were employed in the simulation.

The 2×2 supercell for FeS_2 (200) surfaces was built. The vacuum space along the z direction was set as 15 \AA while the cutoff energy was set as 500 eV . The Brillouin zone of the supercell was sampled by a $3 \times 3 \times 1$ k -point sampling grid and the convergence tolerances of energy and force was set $1.0 \times 10^{-4} \text{ eV per atom}$ and $10^{-2} \text{ eV \AA}^{-1}$, respectively. The DFT-D3 method was used to describe van der Waals interaction.^[50] Spin polarization was included to describe the magnetic properties. The structure for Li_2S_2 was adequately optimized in a $15 \text{ \AA} \times 15 \text{ \AA} \times 15 \text{ \AA}$ vacuum unit cell. The binding energy (E_b) of LiPSs on FeS_2 (200) surfaces was calculated by following equation

$$E_b = E_{\text{sub+LiPS}} - E_{\text{LiPS}} - E_{\text{sub}} \quad (3)$$

where $E_{\text{sub+LiPS}}$ is the total energy of the FeS_2 surface with adsorbed LiPS, E_{LiPS} is the total energy of certain LiPS, and E_{sub} is the total energy of FeS_2 .

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

Acknowledgements

W.S. and S.L. contributed equally to this work. The authors acknowledge the financial support from the Natural Science Foundation of Hunan Province (Nos. 2022JJ40551 and 2022JJ30663), National University of Defense Technology (Grant No. ZK19-27), and Significant Independent Research Projects for Young Talents of College of Aerospace Science and Engineering, National University of Defense Technology.

Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Keywords

electrocatalyses, high energy densities, high sulfur loading, lithium–sulfur batteries, pouch cells

Received: May 13, 2022

Revised: July 27, 2022

Published online:

- [1] F. Wu, J. Maier, Y. Yu, *Chem. Soc. Rev.* **2020**, *49*, 1569.
 [2] Z. P. Cano, D. Banham, S. Ye, A. Hintennach, J. Lu, M. Fowler, Z. Chen, *Nat. Energy* **2018**, *3*, 279.
 [3] P. Yan, J. Zheng, J. Liu, B. Wang, X. Cheng, Y. Zhang, X. Sun, C. Wang, J.-G. Zhang, *Nat. Energy* **2018**, *3*, 600.
 [4] W. Sun, Y. Li, K. Xie, S. Luo, G. Bai, X. Tan, C. Zheng, *Nano Energy* **2018**, *54*, 175.
 [5] H. Li, Y. Tao, C. Zhang, D. Liu, J. Luo, W. Fan, Y. Xu, Y. Li, C. You, Z. Z. Pan, *Adv. Energy Mater.* **2018**, *8*, 1703438.

- [6] M. Zhao, B.-Q. Li, X. Chen, J. Xie, H. Yuan, J.-Q. Huang, *Chem* **2020**, *6*, 3297.
 [7] W. Deng, J. Phung, G. Li, X. Wang, *Nano Energy* **2021**, *82*, 105761.
 [8] J. Xu, S. An, X. Song, Y. Cao, N. Wang, X. Qiu, Y. Zhang, J. Chen, X. Duan, J. Huang, *Adv. Mater.* **2021**, *33*, 2105178.
 [9] Z. Du, X. Chen, W. Hu, C. Chuang, S. Xie, A. Hu, W. Yan, X. Kong, X. Wu, H. Ji, *J. Am. Chem. Soc.* **2019**, *141*, 3977.
 [10] J. He, A. Bhargava, A. Manthiram, *Adv. Mater.* **2020**, *32*, 2004741.
 [11] C.-X. Zhao, X.-Y. Li, M. Zhao, Z.-X. Chen, Y.-W. Song, W.-J. Chen, J.-N. Liu, B. Wang, X.-Q. Zhang, C.-M. Chen, *J. Am. Chem. Soc.* **2021**, *143*, 19865.
 [12] D. Fang, Y. Wang, C. Qian, X. Liu, X. Wang, S. Chen, S. Zhang, *Adv. Funct. Mater.* **2019**, *29*, 1900875.
 [13] H. Ye, J. Sun, S. Zhang, H. Lin, T. Zhang, Q. Yao, J. Y. Lee, *ACS Nano* **2019**, *13*, 14208.
 [14] C. Ma, Y. Zhang, Y. Feng, N. Wang, L. Zhou, C. Liang, L. Chen, Y. Lai, X. Ji, C. Yan, *Adv. Mater.* **2021**, *33*, 2100171.
 [15] H. Zhang, L. Yang, P. Zhang, C. Lu, D. Sha, B. Yan, W. He, M. Zhou, W. Zhang, L. Pan, *Adv. Mater.* **2021**, *33*, 2008447.
 [16] B. Jiang, Y. Qiu, D. Tian, Y. Zhang, X. Song, C. Zhao, M. Wang, X. Sun, H. Huang, C. Zhao, *Adv. Energy Mater.* **2021**, *11*, 2102995.
 [17] Z. Ye, Y. Jiang, L. Li, F. Wu, R. Chen, *Adv. Mater.* **2020**, *32*, 2002168.
 [18] J. Wang, Y. Zhao, G. Li, D. Luo, J. Liu, Y. Zhang, X. Wang, L. Shui, Z. Chen, *Nano Energy* **2021**, *84*, 105891.
 [19] J. Liu, S. H. Xiao, Z. Zhang, Y. Chen, Y. Xiang, X. Liu, J. S. Chen, P. Chen, *Nanoscale* **2020**, *12*, 5114.
 [20] J. Liu, S. Xiao, X. Liu, R. Wu, X. Niu, Y. Xiang, J. S. Chen, C. Yang, *Chem. Eng. J.* **2021**, *423*, 130246.
 [21] W. Sun, C. Liu, Y. Li, S. Luo, S. Liu, X. Hong, K. Xie, Y. Liu, X. Tan, C. Zheng, *ACS Nano* **2019**, *13*, 12137.
 [22] Y. Wang, R. Zhang, Y.-c. Pang, X. Chen, J. Lang, J. Xu, C. Xiao, H. Li, K. Xi, S. Ding, *Energy Storage Mater.* **2019**, *16*, 228.
 [23] Z. Shen, M. Cao, Z. Zhang, J. Pu, C. Zhong, J. Li, H. Ma, F. Li, J. Zhu, F. Pan, *Adv. Funct. Mater.* **2020**, *30*, 1906661.
 [24] X. Chen, S. Zeng, H. Muheiyati, Y. Zhai, C. Li, X. Ding, L. Wang, D. Wang, L. Xu, Y. He, *ACS Energy Lett.* **2019**, *4*, 1496.
 [25] J. Shen, X. Xu, J. Liu, Z. Wang, S. Zuo, Z. Liu, D. Zhang, J. Liu, M. Zhu, *Adv. Energy Mater.* **2021**, *11*, 2100673.
 [26] Y. Zhang, G. Li, J. Wang, G. Cui, X. Wei, L. Shui, K. Kempa, G. Zhou, X. Wang, Z. Chen, *Adv. Funct. Mater.* **2020**, *30*, 2001165.
 [27] F. Wu, Y.-S. Ye, J.-Q. Huang, T. Zhao, J. Qian, Y.-Y. Zhao, L. Li, L. Wei, R. Luo, Y.-X. Huang, *ACS Nano* **2017**, *11*, 4694.
 [28] Z. Liang, J. Shen, X. Xu, F. Li, J. Liu, B. Yuan, Y. Yu, M. Zhu, *Adv. Mater.* **2022**, *34*, 2200102.
 [29] Y. Xiao, S. Guo, Y. Ouyang, D. Li, X. Li, W. He, H. Deng, W. Gong, C. Tan, Q. Zeng, *ACS Nano* **2021**, *15*, 18363.
 [30] Z. Jin, T. Lin, H. Jia, B. Liu, Q. Zhang, L. Li, L. Zhang, Z.-M. Su, C. Wang, *ACS Nano* **2021**, *15*, 7318.
 [31] X. Yang, X. Gao, Q. Sun, S. P. Jand, Y. Yu, Y. Zhao, X. Li, K. Adair, L. Y. Kuo, J. Rohrer, *Adv. Mater.* **2019**, *31*, 1901220.
 [32] J.-L. Yang, D.-Q. Cai, Q. Lin, X.-Y. Wang, Z.-Q. Fang, L. Huang, Z.-J. Wang, X.-G. Hao, S.-X. Zhao, J. Li, *Nano Energy* **2021**, *91*, 106669.
 [33] D. Zheng, Z. Jing, Q. Zhao, Y. Kim, P. Li, H. Xu, Z. Li, J. Lin, *Chem. Eng. J.* **2020**, *402*, 125069.
 [34] Y. Cao, S. Huang, Z. Peng, F. Yao, X. Li, Y. Liu, H. Huang, M. Wu, *J. Mater. Chem. A* **2021**, *9*, 3464.
 [35] K. Xi, D. He, C. Harris, Y. Wang, C. Lai, H. Li, P. R. Coxon, S. Ding, C. Wang, R. V. Kumar, *Adv. Sci.* **2019**, *6*, 1800815.
 [36] R. Li, H. Shen, E. Pervaiz, M. Yang, *Chem. Eng. J.* **2021**, *404*, 126462.
 [37] Y. Liu, Y. Barnscheidt, M. Peng, F. Bettels, T. Li, T. He, F. Ding, L. Zhang, *Adv. Sci.* **2021**, *8*, 2101182.

- [38] L. Shi, S.-M. Bak, Z. Shadike, C. Wang, C. Niu, P. Northrup, H. Lee, A. Y. Baranovskiy, C. S. Anderson, J. Qin, *Energy Environ. Sci.* **2020**, *13*, 3620.
- [39] C. Zhao, G.-L. Xu, Z. Yu, L. Zhang, I. Hwang, Y.-X. Mo, Y. Ren, L. Cheng, C.-J. Sun, Y. Ren, *Nat. Nanotechnol.* **2021**, *16*, 166.
- [40] W. Yang, W. Yang, F. Ding, L. Sang, Z. Ma, G. Shao, *Carbon* **2017**, *111*, 419.
- [41] C. Zhou, X. Li, H. Jiang, Y. Ding, G. He, J. Guo, Z. Chu, G. Yu, *Adv. Funct. Mater.* **2021**, *31*, 2011249.
- [42] D. Cai, B. Liu, D. Zhu, D. Chen, M. Lu, J. Cao, Y. Wang, W. Huang, Y. Shao, H. Tu, *Adv. Energy Mater.* **2020**, *10*, 1904273.
- [43] Z. Man, P. Li, D. Zhou, Y. Wang, X. Liang, R. Zang, P. Li, Y. Zuo, Y. M. Lam, G. Wang, *Nano Lett.* **2020**, *20*, 3769.
- [44] Z. Qiao, Y. Zhang, Z. Meng, Q. Xie, L. Lin, H. Zheng, B. Sa, J. Lin, L. Wang, D. L. Peng, *Adv. Funct. Mater.* **2021**, *31*, 2100970.
- [45] B. Liu, S. Huang, D. Kong, J. Hu, H. Y. Yang, *J. Mater. Chem. A* **2019**, *7*, 7604.
- [46] G. Kresse, D. Joubert, *Phys. Rev. B* **1999**, *59*, 1758.
- [47] G. Kresse, J. Furthmüller, *Comp. Mater. Sci.* **1996**, *6*, 15.
- [48] G. Kresse, J. Furthmüller, *Phys. Rev. B* **1996**, *54*, 11169.
- [49] J. P. Perdew, K. Burke, M. Ernzerhof, *Phys. Rev. Lett.* **1996**, *77*, 3865.
- [50] K. Lee, É. D. Murray, L. Kong, B. I. Lundqvist, D. C. Langreth, *Phys. Rev. B* **2010**, *82*, 081101.
- [51] Z. Li, Q. He, X. Xu, Y. Zhao, X. Liu, C. Zhou, D. Ai, L. Xia, L. Mai, *Adv. Mater.* **2018**, *30*, 1804089.
- [52] H. Zhang, L. K. Ono, G. Tong, Y. Liu, Y. Qi, *Nat. Commun.* **2021**, *12*, 4738.
- [53] S. Wang, S. Feng, J. Liang, Q. Su, F. Zhao, H. Song, M. Zheng, Q. Sun, Z. Song, X. Jia, *Adv. Energy Mater.* **2021**, *11*, 2003314.