Biomass porous carbon-based composite for high performance supercapacitor

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Abstract

Biomass porous carbons with abundant pore structure, surface functional groups, and excellent electrical conductivity, are widely used for electrode materials. In this work, biomass carbon with 3D mesh structure was loaded with metal sulfide to synthesize porous carbon-based ultrathin Ni$_3$S$_2$ layered nanosheet structure supercapacitor composite material electrode. C/Ni$_3$S$_2$-16 showed 600 F g$^{-1}$ of high specific capacitance with 20 A g$^{-1}$ current density. After 5,000 charge and discharge cycles, 88.8% of the maximum (initial) specific capacitance was maintained at 10 A g$^{-1}$. The assembled C/Ni$_3$S$_2$-16/C asymmetric supercapacitor achieved an energy density of up to 35.7 Wh Kg$^{-1}$, which was remained at 27.9 Wh Kg$^{-1}$ with a high power density at 1500 W Kg$^{-1}$. Developed pore structure of biomass porous carbon provide sufficient space for the electrolyte in and out of the electrode, therefore the potentially high electrochemical activity and energy density of the transition metal sulfide were fully exhibited.

1. Introduction

Carbon material is the most widely used as electrode material in the field of supercapacitor, with good conductivity, abundant pore structure, good corrosion resistance, low thermal expansion coefficient and low density. Nonetheless, the problems of low capacitance and low energy limit its further development [1]. Therefore, the pseudo–capacitive electrode material is introduced into the carbon material, which synergistically complements each other and synthesizes a carbon-based pseudo–capacitive composite material with high energy density, high conductivity, good rate performance and cycle stability [2–4]. Porous carbon obtained from biomass has become a promising electrode material for its advantages such as cheap cost and multistage pore network structure, which composites with pseudo–capacitive material to improve the electrochemical performance has become a research hotspot [5].

Many studies [6–9] have shown that Ni$_3$S$_2$ is a kind of layered sulfide with excellent performance such as large theoretical capacity, good rate performance and good conductivity, which can be applied in electrochemical energy areas, photocatalysis areas, and so on. Dai et al used carbon nanotubes to composite granular Ni$_3$S$_2$. The prepared supercapacitor obtained high capacitance, but the rate performance was poor [10]. Chou et al prepared a foamed nickel-based sheet-like Ni$_3$S$_2$ electrode material by electrodeposition, and obtained 717 F g$^{-1}$ specific capacitance at 2 A g$^{-1}$. It had perfect cycle performance at a large current density (4 A g$^{-1}$) [11]. For the sake of higher specific capacitance, rate performance, cycle stability and other electrochemical properties, the current research of Ni$_3$S$_2$ is mainly to improve the active surface of nanomaterials by controlling the morphology of the materials.

In this paper, the biomass porous carbon (C) was prepared from the rice husk charcoal, which was by-product of power generation by gasification. Industrial composition analysis results shows that the gasified rice husk carbon contains 49.3% fixed carbon and 46.3% ash content (silicon dioxide). The porous carbon prepared by gasified rice husk charcoal without carbonization process, realizing the secondary utilization of rice husk energy conversion after the gasification power generation, and possessing environmental protection and
economic benefits. Based on the pore structure of biomass carbon itself, and by carbon-silicon separation of biomass carbon, primary pore-rich carbon material was obtained, and then porous carbon with multiscale pore structure prepared with physicochemical activation method. The three-dimensional network structure of porous carbon had a good dispersion effect on metal sulfides. The electrode (C/Ni₃S₂) was manufactured directly on the current collector by hydrothermal method. Then, an asymmetric supercapacitor was made up of the composite and the biomass porous carbon, which has the advantages of environmentally friendly, high efficiency and low cost. The coupling effect of the active surface of the carbon and metal sulfides enhanced the electrochemical performance of the porous carbon based composite electrode and the assembled supercapacitor.

2. Experimental

2.1. Materials
The rice husk charcoal was gotten from Xinquan Rice Co., Ltd of Hefei, China. Ni(NO₃)₂·6H₂O, Ni foam, NH₂CSNH₂, and absolute ethanol, all chemicals were analytically pure.

2.2. Methods
The biomass charcoal was crushed and sifted by 200 mesh, and boiled by the mass fraction of 30% KOH solution at 110 °C for 1 h. Then, the carbon was separated by suction filtration quickly, and calcined in a CO₂ atmosphere at 850 °C for 1 h for physicochemical activation. The activated product was washed by distilled water, 0.5 mol l⁻¹ hydrochloric acid, and boiling distilled water respectively until neutrality, and vacuum drying at 100 °C for 8 h, obtained the porous carbon recorded as C.

3 m mol Ni(NO₃)₂·6H₂O and 3 m mol NH₂CSNH₂ were dissolved in 35 ml of DI water and magnetically stirred. Porous carbon (60 mg) was added and stirred again. The resulting homogeneous solution was then
transferred into a ptfe reactor. Then, 1 cm × 2 cm of acetone and hydrochloric acid treated nickel foam (NF) was put in the reaction mixture. The reaction still was sealed and maintained the temperature of 120 °C with a certain time. NF was removed after cooling at room temperature, deionized water and ethanol rinsed in turn for 3 times, and vacuum drying at 80 °C for 10 h. According to the hydrothermal reaction time of 9, 12 and 16 h, the three C/Ni3S2 composites prepared were recorded as C/Ni3S2-9, C/Ni3S2-12 and C/Ni3S2-16. The preparation of porous carbon and the synthesis of C/Ni3S2 composite material, are shown in figures 1 and 2.

2.3. Characterization
2.3.1. Morphology and structure measurements
Structural identification of C/Ni3S2 was performed by an x-ray diffractometer XRD (D/Max-2200/PC, Rigaku) and a Raman spectrometer (DXR532, Thermo Scientific). The morphologies of the products were examined by SEM (JSM-7600F, JEOL) and TEM (JEM-2100F, JEOL). The surface chemical states were investigated by XPS (Escalab250xi, Thermo Scientific), and fitted the curves with Gaussian function and Lorentz function for analysis.

2.3.2. Electrochemical measurements
Cyclic voltammetry, galvanostatic charging/discharging, and electrochemical impedance spectroscopy, were performed on a CHI 760E electrochemical workstation, and 6.0 mol l⁻¹ KOH was used as the electrolyte. NF-C/Ni3S2 through a one-step hydrothermal reaction as the working electrode, Pt plate and Ag/AgCl as the counter electrode and reference electrode, respectively.

The three-electrode test mainly studies the performance of a single working electrode material, while the two-electrode test evaluates the performance of the entire supercapacitor. C/Ni3S2 composite material was used as the positive electrode, while the biomass porous carbon as the negative electrode to form the asymmetric supercapacitor for two-electrode test.

3. Results
3.1. Structure Analysis of C/Ni3S2
Figure 3 shows the x-ray powder diffraction pattern of C/Ni3S2 composite with scanning rate of 5° min⁻¹ and 2θ range of 10°–80°. The peak near 2θ = 26° is ascribed to the (002) diffraction of graphitic carbon. The (002) peak clearly reveals that the graphitized carbon exists in porous carbon based composite, and the low peak of x-ray diffraction pattern may be due to the low content of porous carbon in the composite or poor crystallinity, while the diffraction peak of other active substances and substrates are too strong. The weak peak at 2θ = 51.7° can be attributed to the standard cubic phase of residual Ni, which is in good agreement with the JCPDS No. 65-2865 [12]. The strong diffraction peaks at 2θ value of 21.7°, 31.1°, 37.8°, 44.3°, 49.7°, 54.6°, 55.1°, 69.0°, 73.0° and 77.9° are identical to the (101), (110), (003), (202), (113), (104), (122), (303), (214) and (401) facets of hexagonal Ni3S2 with lattice constants a = b = 5.745, c = 7.135, which are consistent with the standard phase structure of Ni3S2 (JCPDS No.44-1418) [13], illustrating the C/Ni3S2 composites have been fabricated.
Since the diffraction peak of carbon in the XRD pattern was relatively weak, the composite materials synthesized under different reaction times were further analyzed by Raman spectroscopy, as exhibited in figure 4. Three products with different reaction times have two characteristic peaks at 1341 cm\(^{-1}\) and 1592 cm\(^{-1}\), which represents the D peak and G peak of carbonaceous materials. The D peak evaluates the defect and disorder degree of the porous carbon material, and the G peak represents the graphite-structured carbon caused by the vibration of the sp\(^2\) carbonaceous material [14]. The intensity ratio \(I_G/I_D\) of the G peak and D peak represents the graphitization degree of carbon materials. The higher of the ratio, the graphitization degree and the conductivity are better. The ratio is beneficial to improve the electrode performance [15]. It can be seen that the \(I_G/I_D\) of the composite materials produced at three different times are similar, all around 1.04, and have the same graphite-like structure.

The morphological of the products were test by the scanning electron microscope picture. In figure 5(a), porous carbon formed a nano-sheet ribbon morphology under the 200 nm scale, which helps to improve the electrode performance [16]. Figures 5(b)–(d) shows the scanning electron microscopy image of the C/Ni\(_3\)S\(_2\) composite when the reaction time was 9 h, 12 h, and 16 h at a reaction temperature of 120 °C. According to the
difference reaction time, relatively uniform Ni3S2 nanoparticles were formed, and the dispersion was well supported on the surface of porous carbon after the reaction time reached 9 h, as shown in figure 5(b). When the reaction time was extended to 12 h, the size of Ni3S2 nanoparticles gradually increased, as shown in figure 5(c), which was consistent with the Ostwald ripening mechanism [17]. When the reaction time was extended to 16 h, the product was composed of ultra-thin nanosheets, a large number of nanosheets were connected to each other, forming a criss-crossed feather-like microstructure, can be seen in figure 5(d).

As shown that there are abundant gaps between the nanosheets, which facilitates the movement of electrolyte ions into and out of the active material to form double-layer capacitance [17]. In addition, the electrolyte and the composite material were in better contact, so that the redox reaction occurred and the pseudocapacitance can be produced.

In order to further determine the phase and specific composition of the C/Ni3S2-16 with ultra-thin nanosheet morphology, the sample was characterized by SEM, EDS, TEM and XPS. Figure 6(a) shows the three-dimensional multi-stage pore interconnection network structure of biomass porous carbon at a size of 2 μm. On one hand, the rich pore structure was conducive to the rapid diffusion and absorption of electrolyte ions, forming a stable double-layer capacitance; on the other hand, the skeleton of porous carbon was beneficial to disperse the loaded metal sulfide well, and promoted Faraday redox reaction to generate pseudo-capacitance, and thus enhanced the specific capacitance and the energy density [18]. Figures 6(b)–(c) show the SEM morphology of the C/Ni3S2-16 composite under different magnifications. It can be seen that Ni3S2 was more uniformly loaded in porous carbon, and the nanosheets connected to each other were well dispersed, and there were abundant pore structures between the sheets. Figures 6(d)–(f) show the SEM-based EDS element mapping

Figure 6. SEM images of porous carbon (a), C/Ni3S2-16 (b)–(c), and EDS element mapping of C/Ni3S2-16 (d)–(f).
Figure 7. TEM images of the C/Ni$_3$S$_2$-16.

Figure 8. C/Ni$_3$S$_2$-16 composite: (a) XPS survey scan, (b) C 1s, (c) Ni 2p, and (d) S 2p spectra.

Figure 9. (a) CV curves (80 mV s$^{-1}$), and (b) GCD curves (3 A g$^{-1}$) of C/Ni$_3$S$_2$-9, C/Ni$_3$S$_2$-12 and C/Ni$_3$S$_2$-16.
of the C/Ni$_3$S$_2$-16 composite material, revealing that the main component of the composite material was composed of C elements, while S and Ni were small amount uniformly dispersed in porous carbon.

The C/Ni$_3$S$_2$-16 composite material was analyzed by TEM, and the results are shown in figure 7. As seen from figure 7(a) that C/Ni$_3$S$_2$ nanosheets are very thin and partially transparent, and the wrinkles or corrugations of the nanosheets exhibit a sheet structure. From the HRTEM image of figure 7(b), it can be clearly seen that the crystal structure of C/Ni$_3$S$_2$ is complete, with lattice spacings of 0.41 nm and 0.28 nm, which correspond to (101) and (110) crystal planes of Ni$_3$S$_2$ crystal respectively, indicating the formation of Ni$_3$S$_2$.[19]

Figure 8(a) shows C, O, Ni, and S four elements measured from C/Ni$_3$S$_2$-16 composite material by XPS. Narrow-spectrum scanning of several elements in the composite material and fitting of the peaks are shown in figures 8(b)–(d). The C 1s spectrum of the C/Ni$_3$S$_2$-16 composite material is shown in figure 8(b). There is a sharp peak at 284.7 eV, which can be ascribed to the characteristics of the sp2 graphite lattice (C–C/C=C), and the relative peak area accounts for 48.3% of the carbon-related groups in the composite. The elemental composition and carbon-related groups of the composite obtained by XPS analysis is shown in table 1. Furthermore, the other peaks from 286 eV to 289 eV attribute to the bonds of C–O, C=O, and O–C=O, confirming the existence of porous carbon in the composite material [20].

Figure 8(c) shows the spectra of Ni 2p in C/Ni$_3$S$_2$-16 composite material, which divided into Ni 2p3/2 and Ni 2p1/2 characteristic peaks at 856.1 eV and 873.5 eV, respectively, as well as two satellite peaks [21]. Figure 8(d) is the spectra of S 2p in C/Ni$_3$S$_2$-16 composite material. The S 2p energy spectrum can be divided into two peaks. The peak at 163.8 eV was a typical metal sulfur bond, and the peak at 162.6 eV can be ascribed to sulfur ions with lower surface coordination [22]. These results indicated that Ni$_3$S$_2$ was successfully loaded on porous carbon.

Table 1. Elemental compositions and relative content of carbon-related groups obtained by XPS analysis.

| C/Ni$_3$S$_2$-16 composites | C (%) | O (%) | Ni (%) | S (%) |
|-----------------------------|-------|-------|--------|-------|
| C/Ni$_3$S$_2$               | 46.5  | 35.16 | 13.44  | 4.9   |
| C–C/C=C (%)                 | 48.3  | 20.8  | 12.5   | 18.4  |
3.2. Electrochemical properties

3.2.1. C/Ni3S2 nanocomposite electrode

CV and GCD were tested by the three-electrode in 6.0 mol l\(^{-1}\) KOH alkaline electrolyte on C/Ni3S2 composite materials, which synthesized at different times. Figure 9(a) shows the CV curves of the three samples C/Ni3S2-9, C/Ni3S2-12, C/Ni3S2-16 at 80 mV s\(^{-1}\) sweep speed with the test voltage range of −0.1～0.7 V. As clearly seen that CV curve was not a kind of rectangular curve, generating obvious pseudocapacitive behavior [23]. The performance of the composite materials not only lie on the double electric layer, but also lie on the redox process. The C/Ni3S2-9 sample has the smallest integrated area of the CV curve and has a relatively low specific capacitance, while the C/Ni3S2-16 sample has the largest integrated area and has symmetrical oxidation and reduction peaks. It shows that the redox process between the composites and electrolyte was invertible, and a higher specific capacitance was obtained. This pair of redox peaks of C/Ni3S2-16 can be ascribed to the invertible reaction of Ni(II) ↔ Ni(III) [24] in KOH electrolyte.

At the current density of 3 A g\(^{-1}\), the charge-discharge curves (0～0.5 V) of the heterostructure products C/Ni3S2-9, C/Ni3S2-12 and C/Ni3S2-16 can be seen in figure 9(b). Three curves display obvious bending, which indicate the existence of pseudocapacitive behavior, and consistent with the analysis result of cyclic voltammetry curves. The specific capacitance values corresponding to three GCD curves were 436, 492 and 972 F g\(^{-1}\), respectively. The specific capacitance of three samples varies greatly under the condition of large current density, indicating that the electrochemical performance of nano-flake composite material was better than that of nano particles, and nano-flake composite material was more suitable for the electrode material of supercapacitor [16].

For better appraise the electrochemical properties of biomass porous carbon-based composite C/Ni3S2-16, the CV curves of different scanning speeds and GCD of different current densities were tested in 6 mol l\(^{-1}\) KOH, which are shown in figures 10(a) and (b).

As seen that well-described redox peaks were attributed to Ni\(^{2+}\) ↔ Ni\(^{3+}\). Moreover, the CV curves can be well maintained at 80 mV s\(^{-1}\), indicating C/Ni3S2-16 electrode possess a good reversibility and stability. In figure 10(b), the GCD curves of C/Ni3S2-16 electrode with different current densities at the potential window of 0～0.5 V. The specific capacitances were calculated as 974 F g\(^{-1}\), 972 F g\(^{-1}\), 864 F g\(^{-1}\), 724 F g\(^{-1}\), 663 F g\(^{-1}\), and 600 F g\(^{-1}\) corresponding 1.5 A g\(^{-1}\), 3 A g\(^{-1}\), 6 A g\(^{-1}\), 10 A g\(^{-1}\), 15 A g\(^{-1}\), and 20 A g\(^{-1}\) current densities, respectively. The specific capacitance is decreased with the increasing of current density. At the current density of 1 A g\(^{-1}\), the specific capacitance of C/Ni3S2-16 is 1080 F g\(^{-1}\), which is higher than the porous carbon electrode (143 F g\(^{-1}\)) [25] and the porous carbon-based composite C/SnO\(_2\) electrode (228 F g\(^{-1}\)) [26]. Compared with Ni3S2 nanoparticles (911 F g\(^{-1}\) at 0.5 A g\(^{-1}\)) [27], C/Ni3S2-16 electrode also has a higher specific capacitance and a good development prospects.

The capacitance performance of C/Ni3S2-16 as seen in figure 10(c). Up to 80% of the initial capacitance can be retained when the current density increases from 1 A g\(^{-1}\) to 6 A g\(^{-1}\), revealing that the C/Ni3S2-16 electrode has good rate performance. As shown in figure 10(d), the cyclic stability of C/Ni3S2-16 was investigated by 5,000 charging and discharging at 10 A g\(^{-1}\). Remarkably, the specific capacitance of C/Ni3S2-16 electrode gradually increases in the initial cycle, and up to 737.6 F g\(^{-1}\) after 300 cycles, which is related to the full activation of the current electrode. After extended cycling to 5000 cycles, the capacitance can still maintain 88.8% of the highest value, showing superior cycle stability.

Figure 11. Nyquist plots of the C/Ni3S2-16 nanosheet electrode.
EIS measurements were also used to investigate the electrochemical properties of C/Ni$_3$S$_2$-16, as shown in figure 11. The frequency range of AC impedance tests for C/Ni$_3$S$_2$-16 electrode is from 0.1 Hz to 100 kHz, and the direct current (DC) bias voltage is 0. At high frequency region, the equivalent series resistance is 0.63 $\Omega$. The diameter of the arc corresponded to Faradic charge transfer resistance, and the value is extremely low, about 0.05 $\Omega$. A straight line with a slope greater than 45° in the low frequencies, indicating that adsorption/desorption on the electrolyte surface was very rapid due to outstanding ion transport and electron conduct [28].

3.2.2. Asymmetric supercapacitors
In order to further estimate the electrochemical property of C/Ni$_3$S$_2$-16, two-electrode system was tested with C/Ni$_3$S$_2$-16. Due to the connection of C and C/Ni$_3$S$_2$-16 two electrode voltage range, which were -1 $\sim$ 0 V and 0 $\sim$ 0.5 V, therefore the working voltage of the assembled C/Ni$_3$S$_2$-16//C asymmetric supercapacitor in 6 mol l$^{-1}$ KOH solution can reach 1.5 V.

According to positive and negative charges balance, match the mass of positive electrode and negative electrode as follows:

$$\frac{m^+}{m^-} = \frac{C^- \times \Delta V^-}{C^+ \times \Delta V^+}$$

Where m (g) is the quality of the electrode active material, $C$ (F g$^{-1}$) is the specific capacitance, $\Delta V$ (V) is the voltage window.

The optimal mass ratio between C/Ni$_3$S$_2$-16 and porous carbon is calculated to be 0.25. In order to evaluate the exact mass of the C/Ni$_3$S$_2$-16 active materials, the residual Ni-foam framework after hydrothermal reaction was removed after soaking in the FeCl$_3$ solution for 3 days. The fabrication process of the C/Ni$_3$S$_2$-16 sample was optimized through changing reaction temperature and time, the electrochemical results showed that the active materials of C/Ni$_3$S$_2$-16 sample with $\sim$1.5 mg cm$^{-2}$ obtained at 120 °C for 16 h possess the excellent performance and better superior capacitance. So, the exact mass of the porous carbon electrode was about 6.0 mg cm$^{-2}$.

Figure 12(a) compares the CV curves of the two electrodes of C/Ni$_3$S$_2$-16 and C with a scan rate of 60 mV s$^{-1}$ under a stable operating voltage window. Figure 12(b) reveals the CV curves of asymmetric capacitors at sweep speeds of 30, 50, 70, and 90 mV s$^{-1}$, which with obvious redox peaks, indicating pseudocapacitance behavior.
With scan rate increased, current response also increased. When scan rate up to 90 mV s\(^{-1}\), the peak shape can be well maintained, indicating good rate performance.

Figure 12(c) exhibits the GCD curves with different current densities region of 0.2 to 2 A g\(^{-1}\), which are classified into linear scope and plateau scope. The discharge curve in the linear region is the electric double layer capacitance behavior, and the bending of the curve in the plateau region indicates the pseudo capacitance behavior of the redox reaction. The specific capacitances are 114.3 F g\(^{-1}\), 107.2 F g\(^{-1}\), 106 F g\(^{-1}\), 96 F g\(^{-1}\) and 89.3 F g\(^{-1}\), which obtain at current densities of 0.2 A g\(^{-1}\), 0.4 A g\(^{-1}\), 1 A g\(^{-1}\), 1.5 A g\(^{-1}\), 2 A g\(^{-1}\), respectively. Due to the redox reaction of the active substance is weakened at higher current density, so, the capacitance decreases with the increasing of current density. Furthermore, C//Ni\(_3\)S\(_2\)-16/C asymmetric supercapacitor has excellent rate performance. 78.1% of the initial capacitance can be remained. C//Ni\(_3\)S\(_2\)-16/C asymmetric supercapacitor achieves an operating voltage of 1.5 V, which improves the energy density of the supercapacitor. The Ragone diagram is drawn by calculating, as shown in figure 12(d). When the operating voltage is 1.5V and the power density is 150 W kg\(^{-1}\), the energy density is as high as 35.7 Wh Kg\(^{-1}\). And the energy density remains at 27.9 Wh Kg\(^{-1}\) as the power density is 1500 W kg\(^{-1}\), which shows advantages of C//Ni\(_3\)S\(_2\)-16/C and evidently better than those of other metal compounds [29, 30].

Based on the above analysis, C//Ni\(_3\)S\(_2\)-16 composite has good electrochemical performance. Firstly, a multi-stage pore structure of porous carbon [23] and loaded the nanosheet structure of Ni\(_3\)S\(_2\), being beneficial for the faradic reactions and facilitating the adsorption-desorption processes of the charge. Simultaneously, porous carbon also provides active centers of EDLC, leading to a high specific capacitance. Secondly, Ni\(_3\)S\(_2\) has ultrathin nanosheets and open structure, which enhances the touch of electrolyte and electrode, thereby significantly increasing the capacitance. Thirdly, the direct contact between the underlying NF and C//Ni\(_3\)S\(_2\)-16 composite avoids using conductive additives and polymer binder, which reduces the electrode resistance significantly, ensuring the electrode material with high electrochemical utilization rate.

4. Conclusions

In this work, a simple one-step hydrothermal method was used to prepare a three-dimensional biomass porous carbon loaded Ni\(_3\)S\(_2\) nanosheet composite material grown directly on nickel foam. Structure designed by adjusting the reaction time, synthesizing porous carbon-based ultrathin Ni\(_3\)S\(_2\) layered nanosheet structure composite electrode. The network structure of porous carbon was used to avoid the agglomeration of metal sulfide, expanded the active area, and assembled the C//Ni\(_3\)S\(_2\)-16/C asymmetric supercapacitor, which possessed outstanding electrochemical performance.

(1) At the reaction temperature of 120 °C, when the reaction time was extended to 16 h, the product was ultrathin nanosheets. A large number of nanosheets were connected to each other to form a feather-like microstructure, and the gaps between the nanosheets were large. In addition, the electrochemical performance of nano-sheet composites were better than nano-particles, C//Ni\(_3\)S\(_2\)-16 was more suitable as the electrode material of supercapacitors.

(2) The biomass porous carbon with rich pore structure compounded Ni\(_3\)S\(_2\), which leaded to the exposure of more units of the Ni\(_3\)S\(_2\) ultrathin nanosheets, promoted the electrolyte to enter the electrode material, meanwhile, porous carbon also afforded the electric double layer, improved the conductivity, and stabilized the volume structure of the metal sulfide in the electrode material.

(3) C//Ni\(_3\)S\(_2\)-16 exhibited a high specific capacitance of 600 F g\(^{-1}\) at a current density of 20 A g\(^{-1}\). After 5000 charge-discharge cycles at a current density of 10 A g\(^{-1}\), the specific capacitance retention rate was 88.8%. The C//Ni\(_3\)S\(_2\)-16/C asymmetric supercapacitor was assembled. An energy density obtained as high as 35.7 Wh Kg\(^{-1}\) with the power density of 150 Wkg\(^{-1}\), and remained at 27.9 Wh Kg\(^{-1}\) with a high power density at 1500 W kg\(^{-1}\), which showed the advantages of C//Ni\(_3\)S\(_2\)-16/C.

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Additional information

The authors declare no competing interests.
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