Synthesis of Three dimensional Mo-Doped Nickel Sulfide Mesoporous Nanostructures/Ni Foam Composite for Supercapacitor and Overall Water Splitting

Songyang Li,¹ Jincheng Fan,^{1,*} Shidong Li,¹ Hongguang Jin,¹ Wenbin Luo,¹ Yong Ma,^{2,*} Jianghong Wu,^{1,3} Zisheng Chao,^{1,*} Nithesh Naik,⁴ Duo Pan^{5,6} and Zhanhu Guo^{5,*}

Abstract

Three-dimensional (3D) Mo-doped nickel sulfide (Ni_3S_2) mesoporous nanostructures on Ni foam were successfully synthesized via the solvothermal method, which showed superior properties for energy storage and conversion. As an electrode for supercapacitors, 3D Mo-doped Ni_3S_2 mesoporous nanostructures demonstrated a $604.4 \mu\text{Ah cm}^{-2}$ specific capacity and good cycling stability. Furthermore, Mo-doped Ni_3S_2 mesoporous nanostructures exhibited superior hydrogen evolution reaction and oxygen evolution reaction properties and good cycle stability for water splitting. At 1.41 V, the electrolyzer made up of Mo-doped Ni_3S_2 mesoporous nanostructures reached the 10mA cm^{-2} catalytic current density, demonstrating outstanding long-term durability. Furthermore, the physical characterization results and mechanism of the 3D Mo-doped Ni_3S_2 were investigated. Therefore, the study presents the great promise of the 3D Mo-doped Ni_3S_2 mesoporous nanostructures in energy conversion and storage.

Keywords: 3D Mo-doped Ni_3S_2 mesoporous nanostructures; Electrochemical performances; Supercapacitor; Water splitting.

Received: 14 August 2021; Accepted: 03 February 2022.

Article type: Research article.

1. Introduction

Sustainable energy and storage applications have received much attention because of the global energy crisis^[1-6] Supercapacitors and water splitting are necessary due to their unique advantages.^[7-10] Thereinto, the supercapacitor has many desirable performances, such as high power density and excellent stability.^[11-17] The electrochemical properties of a supercapacitor are decided through the electrode material. Accordingly, it is essential to synthesize electrode materials with excellent electrochemical performance.

With its clean efficient and renewable properties, hydrogen is considered an ideal candidate to replace fossil fuels.^[18-25]

Among all hydrogen (H_2) energy technologies, electrocatalytic splitting of water including oxygen evolution reaction (OER) and hydrogen evolution reaction (HER) is considered to be an effective one to prepare clean energy.^[26-32] During the process, the large-scale catalysts play a significantly important role. However, there is a challenge to prepare the electrocatalysts to have high properties as well as good consistency for OER and HER processes.^[33-35]

Recently, transition metal chalcogenides have been widely investigated for supercapacitor and water splitting due to their low cost, earth abundance, and low-temperature synthesis.^[36-38] Among all transition metal chalcogenides, Ni_3S_2 has attracted much attention due to its high electrochemical activity. Many researchers have studied Ni_3S_2 with various morphologies as electrode materials for supercapacitors and overall water splitting.^[39-41] Kim *et al.* prepared the supercapacitor with Ni_3S_2 as the electrode and a 786.5 C g^{-1} specific capacitance at 10 mA cm^{-2} .^[42] Especially, the asymmetric full-cell supercapacitor demonstrated a 39.7 W h kg^{-1} energy density at 833 W kg^{-1} power density. Co-doped Ni_3S_2 was prepared through the hydrothermal sulfuration route, which displayed a 1826.4 F g^{-1} specific capacitance at 2 A g^{-1} and 53.9% rate capability at 20 A g^{-1} .^[43]

¹ College of Materials Science and Engineering, Changsha University of Science and Technology, Changsha, Hunan 410114, China.

² School of Material Science and Engineering, Shandong University of Science and Technology, Qingdao 266590, China.

³ College of Health Science and Environmental Engineering, Shenzhen Technology University, Shenzhen, Guangdong 518118, China.

⁴ Department of Mechanical & Manufacturing Engineering, Manipal Institute of Technology, Manipal Academy of Higher Education, Manipal-576104, Karnataka, India.

When Ni_3S_2 is used to produce H_2 , Ni_3S_2 shows good HER and OER performances. Li *et al.* fabricated Ni_3S_2 bifunctional electrocatalyst by hydrothermal method, which demonstrated the effective HER and OER actives.^[44] They considered that the electrocatalytic splitting of water by Ni_3S_2 could be improved by tailoring the crystallographic facets. In their studies, the as-prepared Ni_3S_2 presented appealing catalytic performances (at $j = 10 \text{ mA cm}^{-2}$, HER: $\eta = 189 \text{ mV}$, OER: $\eta = 296 \text{ mV}$). Fe-doped Ni_3S_2 structures as electrocatalysts were investigated for overall water splitting, revealing a 1.63 V cell voltage at 10 mA cm^{-2} .^[45]

Here, we reported that 3D Mo-doped Ni_3S_2 mesoporous nanostructures were fabricated onto Ni foam (NF) by a solvothermal route. 3D Mo-doped $\text{Ni}_3\text{S}_2/\text{NF}$ exhibited superior electrochemical performances. The supercapacitor based on 3D Mo-doped Ni_3S_2 mesoporous nanostructures demonstrated good areal-specific capacitance, high rate performance, as well as excellent cyclic stability. Besides, 3D Mo-doped Ni_3S_2 mesoporous nanostructures displayed good HER and OER properties having low overpotentials and good cycle stability for water splitting. Especially, the effects of the temperature on electrochemical performances for Ni_3S_2 mesoporous nanostructures were also investigated, systematically. Therefore, the study presents the great promise of the 3D Mo-doped Ni_3S_2 mesoporous nanostructures in energy conversion and storage.

2. Experiment section

2.1 Materials

All chemical reagents were purchased from Sinopharm Chemical Reagent Co., Ltd, and were used directly without further processing.

2.2 Preparation of 3D Mo-doped Ni_3S_2 mesoporous nanostructures on Ni foam

3D Mo-doped Ni_3S_2 mesoporous nanostructures were prepared by a facile solvothermal route. A $1 \text{ cm} \times 2 \text{ cm}$ Ni foam was cleaned to remove the nickel oxides on the surface. To synthesize Ni_3S_2 mesoporous nanostructures, 2.2 g $\text{Na}_2\text{S} \cdot 9\text{H}_2\text{O}$ and 0.01 g MoS_2 were fully dispersed into 20 mL ethanol. Afterward, the solution and Ni foam were put into an autoclave, followed by keeping them at 160°C for 20 h. When it was done, Ni foam was washed and dried. Ni foam was marked S-001. Similarly, another three samples were prepared

in the solution containing 2.2 g $\text{Na}_2\text{S} \cdot 9\text{H}_2\text{O}$ and various contents of 0.02 g, 0.03 g, and 0.04 g MoS_2 , which were separately marked as S-002, S-003, and S-004.

2.3 Materials characterization

X-ray diffractions (XRD) were obtained by a Bruker-D8 diffractometer. The surface morphology was observed by scanning electron microscopy (SEM, Hitachi S-4800) with energy-dispersive spectroscopy (EDS) and Transmission electron microscope (TEM, Tecnai G2 F20). X-ray photoelectron spectroscopy (XPS) spectra were got by a VG Escalab210 spectrometer. Electrochemical performances were measured by employing a CHI660E electrochemical workstation. The sample, Hg/HgO , and Pt electrodes separately served as working, reference, and counter electrodes. Cyclic voltammetry (CV) and galvanostatic charge/discharge (GCD) tests were measured in potential ranges from 0 to 0.8 and 0–0.5 V, respectively, in a 6 M KOH electrolyte solution. Electrochemical impedance spectroscopy (EIS) was conducted over a frequency range from 0.1 Hz to 100 kHz. The areal capacity is obtained by using $C_A = I \times \Delta t / (\Delta V \times S)$, in which I (A), Δt (s), ΔV (V), and S (cm^2) are galvanostatic current, discharging time, potential window, as well as geometric surface area. For HER and OER tests, linear sweep voltammetry (LSV) was used to investigate the HER and OER actives. All the electrode potentials were obtained by $E_{\text{RHE}} = E_{\text{Hg}/\text{HgO}} + 0.059 \text{ pH} + 0.14 \text{ V}$. Overpotentials were got by $\eta = E_{\text{RHE}} - 1.23 \text{ V}$. Tafel slope was got by $\eta = \log j + a$, in which a , j and b are constant, current density as well as Tafel slope.

3. Results and discussion

3.1 Characterization of Mo-doped $\text{Ni}_3\text{S}_2/\text{NF}$

Figure 1 shows the crystal composition of Mo-doped $\text{Ni}_3\text{S}_2/\text{NF}$. In Fig. 1a, the peaks at 21.9° , 31.3° , 37.8° , 49.8° , and 55.4° were detected, assigned to (101), (110), (003), (113) and (122) planes of Ni_3S_2 (PDF No. 654935). All XRD patterns show the peaks at 44.6° , and 52.1° , which well matched the (111) and (200) planes of Ni. Compared to data of pure Ni_3S_2 , the peaks of Mo-doped Ni_3S_2 were slightly shifted towards lower diffraction angles (Fig. 1b) due to the doping of Mo into the lattice of nickel sulfides.^[46–48]

Figure 2, Fig. 3, and Figs. S1–3 displays the SEM images of Mo-doped $\text{Ni}_3\text{S}_2/\text{NF}$ prepared with various MoS_2 contents in reaction solutions. It can be seen that the 3D Mo-doped Ni_3S_2 network covered the surface of Ni foam and presented mesoporous nanostructures with different diameters. Meanwhile, electron energy spectroscopic mapping displays the overlapped distribution of Ni, Mo, S, suggesting the successful doping of Mo (Fig. 4). TEM measurements were conducted to further study the microstructures (Fig. 5). By observing the Mo-doped Ni_3S_2 ultrasonically exfoliated from Ni foam, the clear lattice fringes having 0.238 nm d-spacing was observed, corresponding to (003) plane of Ni_3S_2 and confirmed its excellent crystallinity (Fig. 5b).

⁵ Integrated Composites Laboratory (ICL), Department of Chemical & Biomolecular Engineering, University of Tennessee, Knoxville, TN 37996 USA.

⁶ Key Laboratory of Materials Processing and Mold (Zhengzhou University), Ministry of Education, National Engineering Research Center for Advanced Polymer Processing Technology, Zhengzhou University, Zhengzhou, 450001 China.

*Email: fanjincheng2009@163.com (J. Fan);

courage2010@126.com (Y. Ma); chao_zs@aliyun.com (Z. Chao);

Fig. 1 (a) XRD of Mo-doped Ni_3S_2 prepared onto the surface of Ni foam substrates; (b) magnified XRD in 15° – 40° .

XPS measurement was performed to identify the elements in Mo-doped Ni_3S_2 mesoporous nanostructures and characterize the chemical valence states. Fig. 6a shows the typical XPS survey-scan spectrum of Mo-doped Ni_3S_2 , which presented clearly the Ni 2p, Mo 3p, Mo 3d, and S 2p peaks. As shown in Fig. 6b of the Ni 2p spectrum, peaks at 855.5 eV and 873.2 eV are a result of Ni 2p_{3/2} and Ni 2p_{1/2}, indicating coexisted Ni^{2+} and Ni^{3+} .^[49,50] Moreover, another two peaks are viewed at 861.1 eV and 879.2 eV because of the shakeup-type peaks of Ni. Fig. 6c shows the S 2p spectrum, in which the peaks at 162.8 eV and 163.5 eV of metal-sulfur bonds. Besides, one satellite peak at 168.5 eV is also seen, which is assigned to the S-Ni bond.^[47,51] The Mo 3d spectrum consists of three peaks at 226.90 eV, 228.2 eV as well as 232.3 eV by fitting, respectively. The former is indexed to Mo-S, and the latter is caused by Mo^{4+} 3d 5/2 and Mo^{4+} 3d 3/2.^[52]

Fig. 3 SEM images of S-003 with different magnifications: (a) $\times 1000$; (b) $\times 10000$; (c) $\times 30000$; (d) $\times 50000$.

Fig. 2 SEM images of S-001(a), S-002(b), S-003(c) and S-004(d).

Fig. 4 The typical EDS mapping images of Mo-doped Ni_3S_2 mesoporous nanostructures (S-002).

Fig. 5 The TEM (a) and HRTEM (b) images of Mo-doped Ni_3S_2 nanostructures (S-003).

Fig. 6 The typical XPS spectra of Mo-doped Ni_3S_2 mesoporous nanostructures (S-003): (a) the full spectrum; (b) Ni (c) S and (d) elements.

3.2 Electrochemical performances of Mo-doped Ni_3S_2 mesoporous nanostructures/NF

The electrochemical performances of the samples were evaluated (Fig. 7). Fig. 7a shows the CV curves of Mo-doped Ni_3S_2 mesoporous nanostructures grown with different MoS_2 contents. All electrodes exhibited redox peaks in -0.2 V-0.8 V, in accordance with the redox reaction: $\text{Ni/Co-S} \leftrightarrow \text{Ni/Co-S-OH}$.^[43,53] In Fig. 7b, GCD of the samples

was performed at 2.5 mA cm^{-2} within 0-0.5 V. The charging/discharging profiles were observed for all samples, indicating the pseudocapacitive character of Mo-doped Ni_3S_2 mesoporous nanostructures. The discharging duration for S-001, S-002, S-003, and S-004 were 231.7 s, 240.6 s, 398.2 s, and 281.1 s, and the calculated areal capacities were 321.8 , 334.2 , $553.1 \text{ } \mu\text{Ah cm}^{-2}$ as well as $390.4 \text{ } \mu\text{Ah cm}^{-2}$, respectively. To further investigate the conductivity of Mo-doped Ni_3S_2

mesoporous nanostructure, EIS measurements were carried out on the samples. Fig. 7c demonstrates the corresponding Nyquist plots. All the samples exhibit small equivalent series resistance (R_s). In the high-frequency region, the S-003 electrode had lower R_s of 0.495 Ω , compared to S-001 (R_s : 0.643 Ω), S-002 (R_s : 1.919 Ω), and S-004 (R_s : 4.685 Ω). The result indicated S-003 has better electrical conductivity and kinetics of charge transfer. Besides, a semicircle of S-004 was found, revealing a large charge transfer resistance (R_{ct}). In the low-frequency region, S-002 and S-003 displayed straight lines with similar slopes, which were larger than those of S-001 and S-004, suggesting their inferior Warburg resistances (R_w), meaning bad ion diffusion.

Fig. 7d presents the CV curves of S-003 in the range of 10 mV s^{-1} to 50 mV s^{-1} . One can find that the reduction peaks and oxidation peaks shifted to positive and negative potentials

when the scan rate is increased, respectively, remaining in the symmetrical position. The result illustrated the Mo-doped Ni_3S_2 mesoporous nanostructures could experience high current charge/discharge cycles with the reversible redox reaction. The GCD of S-003 was measured, as shown in Fig. 7e. Obviously, well-defined voltage plateaus were detected, suggesting that redox reactions occurred. Besides, the measured curves with symmetric shapes indicated an excellent coulombic efficiency in reversible redox. In the range, the areal capacity value of S-003 gradually became from 604.4 $\mu\text{Ah cm}^{-2}$ to 467.5 $\mu\text{Ah cm}^{-2}$ (Fig. 7f). The capacitive performances of S-001, S-002, and S-004 were also investigated systematically, as shown in Figs. S4-6 and they demonstrated a similar situation to S-003. For S-002, the area capacity became from 393.0 to 274.2 $\mu\text{Ah cm}^{-2}$ (Fig. S5c).

Fig. 7 (a) CV curves at 50 mV s^{-1} , (b) GCD curves at 2.5 mA cm^{-2} , (c) Nyquist curves of S-001, S-002, S-003, and S-004; (d) CV curve and (e) GCD curves and areal capacity of S-003.

Fig. 8 (a) Cycle tests of $\text{Ni}_3\text{S}_2/\text{Ni}$ electrode, (b) XRD patterns of S-003 after 3500 cycles.

The cycle measurement proceeded to investigate the stable ability of Mo-doped Ni_3S_2 mesoporous nanostructures (S-003). The electrode remained 78.3% capacitance retention after 3500 cycles, which demonstrated the excellent cycle stability of Mo-doped Ni_3S_2 mesoporous nanostructures (Fig. 8a). Concurrently, the XRD pattern of S-003 under this test exhibited good crystallinity of Mo-doped Ni_3S_2 mesoporous nanostructures (Fig. 8b).

The effects of measurement temperatures on electrochemical performances were investigated, as shown in

Fig. 9. Obviously, the areas of CV curves at higher measurement temperatures were larger than those of CV curves at lower measurement temperatures, suggesting the higher specific capacitance. Fig. 9b shows the Nyquist plots for S-003 at 0–60 °C, which revealed that charge-transfer resistance decreased from 0.528 Ω (0 °C) to 0.408 Ω (60 °C). As the measurement temperature soared to 60 °C, the areal capacity values increased from 383.5 $\mu\text{Ah cm}^{-2}$ to 779.2 $\mu\text{Ah cm}^{-2}$, which were in agreement with the CV and EIS results.

Fig. 9 The typical CV curves (a), Nyquist plots (b) and GCD profiles (c) for Mo doped $\text{Ni}_3\text{S}_2/\text{NF}$ electrodes (S-003).

Fig. 10 (a) LSV HER of Mo doped $\text{Ni}_3\text{S}_2/\text{NF}$ electrodes; (b) HER overpotential values at 10 mA cm^{-2} ; (c) Tafel curves of HER.

The 3D interconnected Mo-doped Ni_3S_2 mesoporous nanostructures/NF were also investigated at 5 mV s^{-1} to make water splitting. The LSV curves were listed in Fig. 10. At 10 mA cm^{-2} , The overpotentials for S-001, S-002, S-003, and S-004 are 96 mV, 107 mV, 104 mV and 120 mV (Fig. 10b), lower than those of NiCoP (150 mV)^[54] and Ni_2P nanotubes (150

Fig. 11 (a) LSV OER for Mo-doped $\text{Ni}_3\text{S}_2/\text{NF}$ electrodes; (b) OER overpotential values at 20 mA cm^{-2} ; (c) Tafel curves of OER.

mV).^[55] The Tafel slopes of S-001, S-002, S-003, and S-004 were 71 mVdec⁻¹, 91 mVdec⁻¹, 104 mVdec⁻¹, and 181 mVdec⁻¹, respectively, suggesting favorable HER kinetics (Fig. 10c). Furthermore, the durability of Mo-doped Ni₃S₂ mesoporous nanostructures/NF was investigated by i-t measurement. Fig. 10d presents the typical i-t curve of Mo-doped Ni₃S₂ mesoporous nanostructures/NF, which delivered 10 mA cm⁻²

after 10 h and demonstrated the stable HER catalytic properties. Remarkably, the almost unchanged LSV curves further verified the super satisfactory durability (Fig. 10d: inset).

In addition, Mo-doped Ni₃S₂ mesoporous nanostructures/NF delivered good OER properties. Fig. 11a displayed the LSV curves of S-001, S-002, S-003 and S-004

Fig. 12 LSV curves for Mo doped Ni₃S₂/NF electrodes at various measurement temperatures: HER and OER curves at 0-60 °C: (a) (b) S-001; (c) (d) S-002; (e) (f) S-003; (g) (h) S-004.

Fig. 13 Water-splitting polarization of S-001 for (a) anode and (b) cathode, (c) durability of water splitting for S-001, inset of (c) demonstrating the gas evolution.

electrodes. The S-002 electrode demonstrated the super OER activities with the lower overpotential of 160 mV at 20 mA cm⁻², in comparison with S-001 (240 mV), S-003 (230 mV) and S-004 (280 mV) (Fig. 11b). Tafel plots were employed to research the OER kinetics, as shown in Fig. 10c. The Tafel slopes for the electrode were calculated to be 192 mVdec⁻¹ for S-001, 128 mVdec⁻¹ for S-002, 89 mVdec⁻¹ S-003 for and 233 mVdec⁻¹ for S-004, respectively, revealing the favorable OER reaction kinetics (Fig. 11c).

The electrocatalytic properties of Mo-doped Ni₃S₂ mesoporous nanostructures/NF at different temperatures were further estimated. Fig. 12 shows the HER and OER behaviors of S-001, S-002, S-003, and S-004 at various temperatures. HER and OER activities for the samples presented similar changes with increasing temperature: HER and OER curves shift to the higher and lower potential, respectively. These results contributed to the external energy-enhancing HER and OER reactions. At 20 mA cm⁻², HER overpotentials changed from 254 to 138 mV for S-001, 269 to 166 mV for S-002, 238 to 97 mV for S-003, and 247 to 117 mV for S-004, respectively. At 40 mA cm⁻², OER overpotentials changed from 256 to 225 mV for S-001, 326 to 261 mV for S-002, 351 to 271 mV for S-003, and 247 to 117 mV for S-004. This result shows the measurement temperature should be increased properly to enhance HER and OER activities. Based on the above experimental results, the Mo-doped Ni₃S₂ mesoporous

nanostructures/NF hold excellent performances of HER and OER. Consequently, an electrolyzer was assembled with Mo-doped Ni₃S₂ mesoporous nanostructures/NF (S-001) for water splitting. As shown in Fig. 13a, the required voltage for S-001 of 10 mA cm⁻² was 1.41 V for the anode -1.68 V and for the cathode. Moreover, the electrolyzer demonstrated a 40 mA cm⁻² at -1.78 V for 10 h, suggesting its outstanding long-term durability. Remarkably, O₂ and H₂ bubbles were seen at the periphery of the electrode by unaided eyes when the electrolyzer was working (Fig. 13c inset).

4. Conclusions

Here, 3D Mo-doped Ni₃S₂ mesoporous nanostructures were synthesized on the periphery of Ni foam via a solvothermal approach. Their structure and electrochemical performances were investigated, systematically. Mo-doped Ni₃S₂ mesoporous nanostructures demonstrated excellent electrochemical performances for energy storage and conversion. As electrode materials, Mo-doped Ni₃S₂ mesoporous nanostructures delivered an exceptional 604.4 μAh cm⁻² specific capacitance as well as a very promising cyclic stability. Besides, 3D Mo-doped Ni₃S₂ mesoporous nanostructures also demonstrated superior HER and OER properties with low overpotentials and good stability, indicating the potential application in water splitting. Therefore, the study presents the great promise of the 3D Mo-

doped Ni₃S₂ mesoporous nanostructures in energy conversion and storage.

Acknowledgments

Financial support is acknowledged by the program from the National Natural Science Foundation of China (Grant No. 51701022), the Natural Science Foundation of Hu'nan Province (Grant No. 2018JJ3528), Foundation of Hu'nan Educational Committee (Grant No. 18A149), Research and innovation projects for Postgraduates of Hu'nan Province (CX20200903), the International Collaboration Program, CSUST (No. 2018IC28) and the Creative Program from College of Materials Science and Engineering, CSUST.

Conflict of Interest

There is no conflict of interest.

Supporting Information

Applicable.

References

- [1] J. M. Serra, J. F. Borrás-Morell, B. García-Baños, M. Balaguer, P. Plaza-González, J. Santos-Blasco, D. Catalán-Martínez, L. Navarrete, J. M. Catalá-Civera, *Nature Energy*, 2020, **5**, 910-919, doi: 10.1038/s41560-020-00720-6.
- [2] S. Fleischmann, J. B. Mitchell, R. Wang, C. Zhan, D. E. Jiang, V. Presser, V. Augustyn, *Chemical Reviews*, 2020, **120**, 6738-6782, doi: 10.1021/acs.chemrev.0c00170.
- [3] Y. Ma, Z. Zhuang, M. Ma, Y. Yang, W. Li, J. Lin, M. Dong, S. Wu, T. Ding, Z. Guo, *Polymer*, 2019, **182**, 121808, doi: 10.1016/j.polymer.2019.121808.
- [4] Y. Wang, Y. Liu, C. Wang, H. Liu, J. Zhang, J. Lin, J. Fan, T. Ding, J. E. Ryu, Z. J. E. S. Guo, *Engineered Science*, 2020, **9**, 50-59, doi: 10.30919/es8d903.
- [5] J. Cai, W. Xu, Y. Liu, Z. Zhu, G. Liu, W. Ding, G. Wang, H. Wang, Y. J. E. S. Luo, *Engineered Science*, 2019, **5**, 21-29, doi: 10.30919/es8d669.
- [6] L. Xiao, H. Qi, K. Qu, C. Shi, Y. Cheng, Z. Sun, B. Yuan, Z. Huang, D. Pan, Z. Guo, *Advanced Composites and Hybrid Materials*, 2021, **4**, 306-316, doi: 10.1007/s42114-021-00223-2.
- [7] P. Simon, Y. Gogotsi, *Nature Materials*, 2020, **19**, 1151-1163, doi: 10.1038/s41563-020-0747-z.
- [8] M. Yi, B. Lu, X. Zhang, Y. Tan, Z. Zhu, Z. Pan, J. Zhang, *Applied Catalysis B: Environmental*, 2021, **283**, 119635, doi: 10.1016/j.apcatb.2020.119635.
- [9] Z. Li, Z. Lv, X. Liu, G. Wang, Y. Lin, G. Xie, L. Jiang, *Renewable Energy*, 2021, **165**, 612-618, doi: 10.1016/j.renene.2020.11.083.
- [10] R. J. Deokate, *ES Materials & Manufacturing*, 2020, **11**, 16-19, doi: 10.30919/esmm5f938.
- [11] G. Huang, Q. Geng, B. Xing, Y. Liu, Y. Li, Q. Liu, J. Jia, L. Chen, C. Zhang, *Journal of Power Sources*, 2020, **449**, 227506, doi: 10.1016/j.jpowsour.2019.227506.
- [12] Y. Ma, M. Ma, X. Yin, Q. Shao, N. Lu, Y. Feng, Y. Lu, E. K. Wujcik, X. Mai, C. Wang, Z. Guo, *Polymer*, 2018, **156**, 128-135, doi: 10.1016/j.polymer.2018.09.051.
- [13] Y. Tian, X. Yang, A. Nautiyal, Y. Zheng, Q. Guo, J. Luo, X. Zhang, *Advanced Composites and Hybrid Materials*, 2019, **2**, 151-161, doi: 10.1007/s42114-019-0075-4.
- [14] S. S. Patil, T. S. Bhat, A. M. Teli, S. A. Bknalkar, S. B. Dhavale, M. M. Faras, M. M. Karanjkar, P. S. Patil, *Engineered Science*, 2020, **12**, 38-51, doi: 10.30919/es8d1140.
- [15] Y. Ma, C. Hou, H. Zhang, Q. Zhang, H. Liu, S. Wu, Z. Guo, *Electrochimica Acta*, 2019, **315**, 114-123, doi: 10.1016/j.electacta.2019.05.073.
- [16] Z. Zhuang, W. Wang, Y. Wei, T. Li, M. Ma, Y. Ma, *Advanced Composites and Hybrid Materials*, 2021, **4**, 938-945, doi: 10.1007/s42114-021-00225-0.
- [17] Y. Wei, W. Luo, X. Li, Z. Lin, C. Hou, M. Ma, J. Ding, T. Li, Y. Ma, *Electrochimica Acta*, 2022, **406**, 139874, doi: 10.1016/j.electacta.2022.139874.
- [18] Q. Wang, Y. Ma, X. Liang, D. Zhang, M. Miao, *Chemical Engineering Journal*, 2019, **371**, 145-153, doi: 10.1016/j.cej.2019.04.021.
- [19] F. Zhao, Y. Guo, X. Zhou, W. Shi, G. Yu, *Nature Reviews Materials*, 2020, **5**, 388-401, doi: 10.1038/s41578-020-0182-4.
- [20] H. F. Wang, L. Chen, H. Pang, S. Kaskel, Q. Xu, *Chemical Society Reviews*, 2020, **49**, 1414-1448, doi: 10.1039/c9cs00906j.
- [21] Z. Caia, P. Wanga, J. Yanga, X. J. E. E. Wanga, *ES Energy & Environment*, 2019, **5**, 22-36, doi: 10.30919/esee8c320.
- [22] P. Vairale, V. Sharma, B. Bade, A. Waghmare, P. Shinde, A. Punde, V. Doiphode, R. Aher, P. Subhash, S. Nair, *Engineered Science*, 2020, **11**, 76-84.
- [23] Y. Ma, C. Hou, H. Zhang, M. Qiao, Y. Chen, H. Zhang, Q. Zhang, Z. Guo, *Journal of Materials Chemistry A*, 2017, **5**, 14041-14052, doi: 10.1039/c7ta03279j.
- [24] W. Luo, Y. Wei, Z. Zhuang, Z. Lin, X. Li, C. Hou, T. Li, Y. Ma, *Electrochimica Acta*, 2022, **406**, 139871, doi: 10.1016/j.electacta.2022.139871.
- [25] Y. Wei, W. Luo, Z. Zhuang, B. Dai, J. Ding, T. Li, M. Ma, X. Yin, Y. Ma, *Advanced Composites and Hybrid Materials*, 2021, **4**, 1082-1091, doi: 10.1007/s42114-021-00323-z.
- [26] L. Yang, L. Huang, Y. Yao, L. Jiao, *Applied Catalysis B: Environmental*, 2021, **282**, 119584, doi: 10.1016/j.apcatb.2020.119584.
- [27] Y. Zhang, H. Guo, X. Li, J. Du, W. Ren, R. Song, *Chemical Engineering Journal*, 2021, **404**, 26483, doi: 10.1016/j.cej.2020.126483.
- [28] N. C. S. Selvam, J. Lee, G. H. Choi, M. J. Oh, S. Xu, B. Lim, P. J. Yoo, *Journal of Materials Chemistry A*, 2019, **7**, 27383-27393, doi: 10.1039/c9ta10664b.
- [29] J. D. Desai, P. K. Baviskar, K. N. Hui, H. M. Pathan, *ES Energy & Environment*, 2018, **2**, 21-30, doi: 10.30919/esee8c208.
- [30] N. Singh, S. Jana, G. P. Singh, R. K. Dey, *Advanced Composites and Hybrid Materials*, 2020, **3**, 127-140, doi: 10.1007/s42114-020-00140-w.

- [31] Y. Wei, M. Zheng, W. Luo, B. Dai, J. Ren, M. Ma, T. Li, Y. Ma, *Journal of Energy Storage*, 2022, **45**, 103715, doi: 10.1016/j.est.2021.103715.
- [32] M. Zheng, Y. Wei, J. Ren, B. Dai, W. Luo, M. Ma, T. Li, Y. Ma, *Separation and Purification Technology*, 2021, **277**, 119455, doi: 10.1016/j.seppur.2021.119455.
- [33] L. He, S. Huang, Y. Liu, M. Wang, B. Cui, S. Wu, J. Liu, Z. Zhang, M. Du, *Journal of Colloid and Interface Science*, 2021, **586**, 538-550, doi: 10.1016/j.jcis.2020.10.119.
- [34] Q. Jin, B. Ren, H. Cui, C. Wang, *Applied Catalysis B: Environmental*, 2021, **283**, 119643, doi: 10.1016/j.apcatb.2020.119643.
- [35] Y. Deng, H. Liu, X. Wei, L. Ding, F. Jiang, X. Cao, Q. Zhou, M. Xiang, J. Bai, H. Gu, *Journal of Colloid and Interface Science*, 2021, **585**, 800-807, doi: 10.1016/j.jcis.2020.10.060.
- [36] K. Cui, J. Fan, S. Li, M. F. Khadidja, J. Wu, M. Wang, J. Lai, H. Jin, W. Luo, Z. Chao, *Nanoscale Advances*, 2020, **2**, 478-488, doi: 10.1039/c9na00633h.
- [37] W. Zhong, Z. Wang, N. Gao, L. Huang, Z. Lin, Y. Liu, F. Meng, J. Deng, S. Jin, Q. Zhang, L. Gu, *Angewandte Chemie International Edition*, 2020, **59**, 22743-22748, doi: 10.1002/anie.202011378.
- [38] Q. Hu, M. Tang, M. He, N. Jiang, C. Xu, D. Lin, Q. Zheng, *Journal of Power Sources*, 2020, **446**, 227335, doi: 10.1016/j.jpowsour.2019.227335.
- [39] S. Wang, Z. Xiao, S. Zhai, H. Wang, W. Cai, L. Qin, J. Huang, D. Zhao, Z. Li, Q. An, *Journal of Materials Chemistry A*, 2019, **7**, 17345-17356, doi: 10.1039/c9ta05145g.
- [40] X. X. Liu, R. Wu, Y. Wang, S. H. Xiao, Q. He, X. B. Niu, D. J. Blackwood, J. S. Chen, *Electrochimica Acta*, 2019, **311**, 221-229, doi: 10.1016/j.electacta.2019.03.212.
- [41] Z. Shi, L. Yue, X. Wang, X. Lei, T. Sun, Q. Li, H. Guo, W. Yang, *Journal of Alloys and Compounds*, 2019, **791**, 665-673, doi: 10.1016/j.jallcom.2019.03.259.
- [42] D. Kim, P. Karthick Kannan, S. Mateti, C. H. Chung, *ACS Applied Energy Materials*, 2018, **1**, 6945-6952, doi: 10.1021/acsaelm.8b01310.
- [43] P. Zhou, Y. Wu, C. Wang, H. Huang, D. Xing, Y. Liu, Z. Wang, P. Wang, Z. Zheng, H. Cheng, Y. Dai, B. Huang, *Chemical Engineering Journal*, 2021, **403**, 126285, doi: 10.1016/j.cej.2020.126285.
- [44] L. Li, C. Sun, B. Shang, Q. Li, J. Lei, N. Li, F. Pan, *Journal of Materials Chemistry A*, 2019, **7**, 18003-18011, doi: 10.1039/c9ta05578a.
- [45] C. Z. Yuan, Z. T. Sun, Y. F. Jiang, Z. K. Yang, N. Jiang, Z. W. Zhao, U. Y. Qazi, W. H. Zhang, A. W. Xu, *Small*, 2017, **13**, 1604161, doi: 10.1002/sml.201604161.
- [46] J. Li, X. Zhang, Z. Zhang, Z. Li, M. Gao, H. Wei, H. Chu, *Electrochimica Acta*, 2019, **304**, 487-494, doi: 10.1016/j.electacta.2019.03.023.
- [47] C. Du, Y. Men, X. Hei, J. Yu, G. Cheng, W. Luo, *ChemElectroChem*, 2018, **5**, 2564-2570, doi: 10.1002/celec.201800630.
- [48] J. Li, Z. Yang, Y. Lin, J. Wang, F. Jiao, Y. Gong, *New Journal of Chemistry*, 2020, **44**, 8578-8586, doi: 10.1039/d0nj00534g.
- [49] F. Du, Z. Chen, Y. Zhang, H. He, Y. Zhou, T. Li, Z. Zou, *Electrochemistry Communications*, 2019, **99**, 22-26, doi: 10.1016/j.elecom.2018.12.009.
- [50] Z. Cui, Y. Ge, H. Chu, R. Baines, P. Dong, J. Tang, Y. Yang, P. M. Ajayan, M. Ye, J. Shen, *Journal of Materials Chemistry A*, 2017, **5**, 1595-1602, doi: 10.1039/c6ta09853c.
- [51] G. Chen, X. Chen, K. Song, N. Zhao, W. Wang, G. Yin, Y. Liu, *ChemistrySelect*, 2019, **4**, 12328-12332, doi: 10.1002/slct.201902553.
- [52] Y. Cheng, M. Zhai, M. Guo, Y. Yu, J. Hu, *Applied Surface Science*, 2019, **467-468**, 1113-1121, doi: 10.1016/j.apsusc.2018.10.230.
- [53] E. Kamali-Heidari, Z. L. Xu, M. H. Sohi, A. Ataie, J. K. Kim, *Electrochimica Acta*, 2018, **271**, 507-518, doi: 10.1016/j.electacta.2018.03.183.
- [54] J. Li, M. Yan, X. Zhou, Z. Q. Huang, Z. Xia, C. R. Chang, Y. Ma, Y. Qu, *Advanced Functional Materials*, 2016, **26**, 6785-6796, doi: 10.1002/adfm.201670165.
- [55] L. Zeng, K. Sun, X. Wang, Y. Liu, Y. Pan, Z. Liu, D. Cao, Y. Song, S. Liu, C. Liu, *Nano Energy*, 2018, **51**, 26-36, doi: 10.1016/j.nanoen.2018.06.048.

Publisher's Note: Engineered Science Publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.