Versatile MXene integrated assembly for piezoresistive micro-force sensing

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Abstract
MXenes have received tremendous attention for flexible electronics owing to their excellent conductivity, water dispersibility, and mechanical flexibility. However, the sediment from the MXene production process is usually discarded as trash, resulting in low utilization. Here, we present a flexible pressure sensor that enables micro-force sensing and efficient utilization of MXene by confining MXene trash among structured MXene electrodes. Benefiting from the synergistic effect of both the confined micro-conical structure and easily changeable space of MXene trash, the as-designed device can detect extremely subtle pressure of 2.9 Pa, deliver a high sensitivity over 4.08 kPa⁻¹, and exhibit a remarkably fast response time (7 ms). These properties make it suitable for monitoring weak force signals from human wrist pulse and even for detecting dynamic responses associated with acoustic waves. This work provides a reference for the versatile and efficient application of MXene in the same device, showing great potential for sustainable production of next-generation wearable smart electronics.

KEYWORDS
confined microstructure, health monitoring, MXene, piezoresistive pressure sensor, sound detection

1 | INTRODUCTION

The promising applications of flexible and wearable pressure sensors in the fields of personal health monitoring, human–computer interaction, and intelligent robotics have attracted a great deal of research interest because of their superb real-time sensing capabilities, high integration potential, and good conformability to skin.¹–⁶ Usually, the performance of a flexible pressure sensor is evaluated in terms of sensitivity, response speed, and detection limit.⁷,⁸ Optimizing the microstructure of flexible substrates and the conductivity of active materials are common and effective strategies to improve the sensing performance of pressure sensors.⁹,¹⁰ Recent studies have demonstrated that microstructures, such as nano-channels,¹¹ micro-pyramids,¹²,¹³ and hierarchical
fibers, can confer good sensitivity to sensors because they have larger contact areas and more conductive pathways when subjected to forces. However, due to the relatively large modulus of rubber substrates or soft substrates, most of these devices show a limited minimum pressure detection limit (∼100 Pa), causing them to be insensitive to weak signals such as sound, pulse, and so on. Even if these weak signals can be measured, they are often subjected to a significant prestress, which may cause discomfort to human body in long-term detection. In addition, the inherent viscoelasticity and thermal expansion of such soft materials result in a slow response (>100 ms) and thermal perturbation. Therefore, the ability to achieve ultrafast response with low detection limits in piezoresistive sensors remains challenging.

To this end, the introduction of advanced sensing materials contributes to obtaining high-performance piezoresistive pressure sensors. For example, carbon materials, cellulose-based materials, metallic materials, and conducting polymers have been widely used to develop flexible piezoresistive sensors. Among them, two-dimensional transition metal carbides and nitrides (MXenes) have proved to be promising candidates for advanced pressure sensors due to variable layer spacing, high electrical conductivity, easy processing, and rich functional groups. To date, Ti₃C₂Tₓ is the most widely studied MXene and can be obtained by selective etching of Al elements in Ti₃AlC₂. Specifically, 2 g of LiF and 40 mL of HCl (mix 30 mL of 12 M HCl with 10 mL of water) were mixed and stirred for 30 min, then 2 g of Ti₃AlC₂ was added to the solution and magnetically stirred at 40 °C for 24 h. The acidic suspension was washed by centrifugation with Milli-Q water until the pH > 6. Finally, the bottom sediment was collected and dried in a vacuum oven at 40 °C for 12 h. Next, 0.4 g of the dried powder was added to Milli-Q water and processed with ultrasonication for 1 h. Then the treated solution was centrifuged at 3500 rpm for 1 h and the supernatant was removed for MXene nanosheets. The sediment (MXene trash) at the bottom of the centrifuge tube was dried and reserved for use. The concentration of MXene nanosheet solution was obtained by inverse extrapolation from weighing the sediment (MXene trash) after drying.

2.1 | Materials

The MAX (Ti₃AlC₂, 400 mesh) powder was purchased from Jilin 11 Company. The HCl (12 M) and absolute ethyl alcohol were purchased from Chengdu Chron Chemicals. The LiF was obtained from Aladdin Reagent Company. Milli-Q water (17 MΩ, resistivity) was used for centrifugation and washing.

2.2 | Synthesis of MXene nanosheets and MXene trash

MXene (Ti₃C₂Tₓ) was synthesized by selective etching of aluminum (Al) in Ti₃AlC₂. Specifically, 2 g of LiF and 40 mL of HCl (mix 30 ml of 12 M HCl with 10 mL of water) were mixed and stirred for 30 min, then 2 g of Ti₃AlC₂ was added to the solution and magnetically stirred at 40 °C for 24 h. The acidic suspension was washed by centrifugation with Milli-Q water until the pH > 6. Finally, the bottom sediment was collected and dried in a vacuum oven at 40 °C for 12 h. Next, 0.4 g of the dried powder was added to Milli-Q water and processed with ultrasonication for 1 h. Then the treated solution was centrifuged at 3500 rpm for 1 h and the supernatant was removed for MXene nanosheets. The sediment (MXene trash) at the bottom of the centrifuge tube was dried and reserved for use. The concentration of MXene nanosheet solution was obtained by inverse extrapolation from weighing the sediment (MXene trash) after drying.

2.3 | Etching process of the PI film

The structured PI film (thickness: 50 μm) was fabricated by a cold laser marking machine (UV-3S, China). The marking current was set to 8 A, and the distance between cones was 50 μm. Finally, the hydrophilicity of the PI film was enhanced by oxygen plasma treatment (15 min).

2.4 | Fabrication of the flexible pressure sensor

The previously obtained supernatant was configured to 4 mg/mL, which was then sprayed onto the structured PI film to obtain a film with resistance less than 20 Ω/□. After that, the sprayed film was cut into several circular shape with a radius of 0.56 mm. Meanwhile, 0.05 g of MXene trash was added to 1 mL of absolute ethyl
alcohol and sonicated for 40 min to homogenize the dispersion. Then, the MXene trash solution was dropped onto the structured film and dried for 10 min. Next, the two structured films were stacked on top of each other, and conductive carbon cloth was attached to the film. Finally, the device was encapsulated with polyurethane tape.

2.5 Characterization and measurement

The morphologies and structure of MXene and PI film were measured by a Prime scanning electron microscope (SEM, JSM-7800) at an accelerating voltage of 5 kV. Raman spectra of MXene nanosheets and MXene trash were studied using Raman microscopy with a 532 nm laser. X-ray diffractometer (XRD) patterns were used to determine the basic phase and composition of MXene, MAX, and MXene trash using Cu Kα sources with a 2θ ranging from 5° to 80°. The I–V relationships under different external pressures were measured by an electrochemical workstation (CH Instruments, CHI660E). Currents were acquired by a low-noise current preamplifier (Stanford Research SR570) at 0.1 V via a data acquisition card (NI PCI-6221). For the pressure test, small homemade objects, bolts, and a linear motor were used for the test. The related biological signals involved in this article were collected from volunteers, the informed consent was obtained before the collection, and the experiments described here were conform to the local ethical requirements.

2.6 Statistical analysis

All the experiments were performed in triplicate. The obtained data were expressed as the mean value ± standard deviation, the statistical significance for multiple groups was analyzed by the one-way ANOVA by Origin software. Reported p values corresponded to p < 0.05.

3 RESULTS AND DISCUSSIONS

3.1 Design and manufacturing of an MXene trash-based pressure sensor

Figures (1A) depicts the whole fabrication process of the designed flexible pressure sensor. First, the polyimide film (PI) is ablated using laser marking to obtain the micro-conical structure. Laser etching has the advantages of fast speed, nontoxic, and large-area fabrication compared to photolithography and 3D printing. As evidenced in Figure (S1), laser etching yields microstructures with excellent homogeneity and can be prepared quickly over large areas (Figure 1B), which provides a convenient way to fabricate flexible pressure sensors. After centrifuging the MXene etched with LiF and HCl, the MXene nanosheets in the supernatant were sprayed on the micro-conical structured PI film as the electrode of the sensor (Figure 1D). Moreover, the sediment of the solution (mainly composed of unexfoliated Ti3C2Tx and unetched MAX) was drop-casted on the prepared film as the sensing material. Then, two such films were sandwiched between the MXene trash to construct the piezoresistive sensor, as schematically shown in Figure (1C). Thanks to the great change in resistance caused by the variable spacing between MXene trash under external forces, the designed piezoresistive sensor shows great potential for the monitoring of various weak forces (Figure 1E).

3.2 Characterization of MXene and substrate structure

The Ti3AlC2 powder used as raw material to prepare MXenes can be regarded as a finely layered MAX phase, as shown in Figure (S2). After selective etching of the Al elements on Ti3AlC2, the obtained Ti3C2Tx shows a distinct layered structure, as shown in the SEM image of Figure (2A). Subsequently, after sonication and centrifugation, the size of MXene nanosheets in the supernatant is less than 1 μm and easily stacked with each other (Figure S3), which also provided the possibility for the subsequent fabrication of electrodes based on MXene nanosheets. The TEM image shown in Figure (2B) indicates that the MXene nanosheets obtained after sonication are ultrathin and transparent. In contrast, the sediment trash shows an irregular morphology with unexfoliated Ti3C2Tx, unetched MAX, layered nanosheets, and particles (Figure 2C). From the Raman spectra of MXene nanosheets and trash, the Eg group vibration of surface functional group and C atoms can be observed at around 381 and 574 cm−1, whereas peaks around 196 and 724 cm−1 were attributed to A1g symmetry out-of-plane vibrations of Ti and C atoms (Figure 2D). These vibrational patterns indicate that Ti3AlC2 was successfully etched. Moreover, the XRD pattern of MXene trash retains the characteristic peaks of MAX, and there is a clear characteristic peak of successfully etched MXene at about 5.8°, which means that the sediment product is mainly composed of unetched MAX and partially unexfoliated MXene even after several washes (Figure 2E). After spraying the supernatant onto the PI film, an intense (002) diffraction peak appeared, indicating that it had been successfully delaminated into MXene nanosheets. To enhance the binding of MXene nanosheets to PI film, plasma treatment was performed. It can be seen that the
water contact angle of the PI film decreased significantly from 66.6° to 22.6°, proving the success of hydrophilic modification (Figure 2F). This is also manifestly confirmed by the SEM image of the substrate after spraying, where the uniformly distributed MXene nanosheets ensure the stability of the electrodes (Figures 2G and S4). In addition, the SEM image of MXene trash randomly distributed in structured films suggests that this confined structure and variable spacing lay the foundation for good sensing performance (Figure 2H). Most importantly, the whole process is simple, achieving a full utilization of MXene (Figure S5), and the resulting MXene-based pressure sensor exhibits good bendability and twist ability (Figure 2I).

3.3 Working principle and sensing performance of MXene-based pressure sensors

To further explore the working mechanism of the as-fabricated sensor, a corresponding model was established to illustrate it (Figure 3A). The whole resistance of the device can be divided into two parts: the interfacial resistance ($R_1$) between the MXene trash and their adjacent electrodes, and the bulk resistance ($R_2$) of the MXene trash. The corresponding circuit is shown in Figure (3C). When pressure is applied, the distance between MXene trash and the spacing between adjacent interlayers in MXenes decreases simultaneously, resulting in a decrease in $R_2$. At the same time, the contact area between the MXenes trash and the MXene electrodes increases, leading to a decrease in $R_1$, which further enhances the current and thus the sensitivity to external forces (Figure 3B). Furthermore, the electrical performance of the as-prepared piezoresistive sensor was studied at a bias voltage of 0.1 V. Its sensitivity is defined as $S = (I - I_0)/I_0/P$, where $I$ and $I_0$ are the current of the sensor with and without external load, respectively, and $P$ represents the applied pressure. As shown in Figure (3D), the $I$–$t$ curve is continuous and stable during the loading and unloading of the force, and the current gradually increases with the pressure, so the sensor can easily determine the applied pressure by the current. The typical $I$–$V$ curve of the sensor shows the good ohmic contact of the device at various static pressures, with the slope varying with pressure, further indicating the change in resistance (Figure 3E). In addition, the sensor exhibits a high sensitivity of 4.08 and 0.4 kPa$^{-1}$, corresponding to two linear regions with the pressure range of 2.9–500.3 and 500.3–1624.8 Pa, respectively. Both of them are far higher than that of the flexible sensor without the MXene trash (0.04 kPa$^{-1}$), as shown in Figure (3F). Such high sensitivity should benefit from the substantial deformation of the micro-conical structure and mutable spacing of MXene trash. In addition, as shown in Figure (3G), a pressure of about 2.9 Pa from plastic ball can still be detected by the as-designed device, again demonstrating its excellent detection capability for the low pressure. The instantaneous sensing response time (7 ms) and recovery time (30 ms) can be observed in the inset diagram (Figure 3H), confirming
that the sensor has a timely response capability, comparable to that of human skin. At the same time, piezoresistive sensors exhibit outstanding uniformity and stability at different frequencies as shown in Figure (31). In addition, the change in current is fast and stable with only small fluctuations over a long period of 6000 cycles (Figure 3J), demonstrating the long-term repeatability of the MXene-based sensor.

### 3.4 Practical applications of the MXene-based sensor

Benefiting from the excellent performance of the designed MXene-based pressure sensor, several applications were successfully demonstrated and explored. For human activity monitoring, the fabricated piezoresistive sensor can be conformally attached to the human wrist to detect the pulse (Figure 4A). As shown in Figure (4B), the pulse can be recorded stably before and after exercise, where the two main peaks are clearly displayed. In addition, the sensor was fixed on a mouse to test the response to pressing and tapping actions (Figure 4C). Both actions can be sensitively detected, proving its excellent response to static and dynamic pressure (Figure 4D). As shown in Figure (4E), when the sensor was tossed and swayed from a high position, its curve exhibited characteristics of damping-like motion (Figure 4F), which may be related to the motion of MXene trash in the micro-conical structure. When the sensor was connected to the program-controlled LEDs, the number of lit LEDs decreased with the weight on the sensor, indicating that the device has good pressure sensing capability and may be used as a control device (Figure 4G). Moreover, the as-fabricated piezoresistive sensors are
FIGURE 3  The working mechanism and sensing performance of the MXene-based pressure sensor. (A) Schematic diagram of the working mechanism of the sensor. (B) Magnified view of the structural area with a reduced spacing of MAX and MXene in the micro-conical structure under external force, resulting in more conductive paths. (C) The equivalent circuit diagram of the pressure sensor. (D) Current response curves of pressure sensor under various pressures. (E) The I–V relationship of the sensor under different external pressures. (F) Sensitivity of the designed piezoresistive sensor. (G) The minimum pressure detection limit of the pressure sensor. (H) The I–t curve indicates the responsive and recovery time of the sensor under 0.35 kPa. (I) Current response of the device at various frequencies. (J) Excellent repeatability after continuous 6000 loading–unloading cycles under 0.25 kPa, indicating good durability sensitive to weak forces and can even convert the pressure of acoustic waves into the corresponding change in resistance (Figure 4H). As displayed in Figure (4I) and Movie (S1), by comparing the three waveforms, including the waveform of the original audio, the waveform recorded by the commercial device, and the waveform recorded by the fabricated MXene-based sensor, it can be seen that the locations of the characteristic peaks in the time-dependent waveforms are essentially the same. Furthermore, after performing a fast Fourier transform as shown in Figure (4J), the corresponding spectrogram shows that the frequency response of the as-developed device is almost identical to that of the original audio, demonstrating excellent acoustic sensing capabilities comparable to the tympanic membrane of commercial recorders. For different biological sounds (frogs chirping and fish spitting bubbles) and physical sounds (alarm bell and wind chime), the developed sensors are also capable of detecting, and the response signals are recorded in Figure (4K–N). As can be seen that there is a high agreement with the original audio, each response has distinct characteristic peaks that make it easy to distinguish different sounds. Above all, the as-developed device achieves full utilization of MXene material and benefits from the excellent performance of the micro-conical structure-confined MXene trash, which shows great potential for micro-force monitoring and provides an attractive pathway for the development of MXene-based flexible electronics.
In summary, we proposed a strategy for an efficient utilization of MXene and developed a flexible MXene-based piezoresistive sensor for micro-force monitoring by confining MXene trash as a sensing material to a micro-conical structured substrate with sprayed MXene nanosheets as electrodes. Benefiting from the synergistic effect of both the confined micro-conical structure and easily changeable space of MXene trash, the as-developed device exhibits an extremely low detection limit (2.9 Pa), provides a high sensitivity of 4.08 kPa⁻¹, a fast response time (7 ms), as well as cycle stability of 6000 cycles. The prepared flexible sensor successfully demonstrated the application of human physiological signal monitoring and sound recording, showing great potential for wearable electronics.
AUTHOR CONTRIBUTIONS
Shenglong Wang: conceptualization, methodology, validation, writing—original draft. Boling Lan: conceptualization, formal analysis, software, methodology. Yuwu Gao: methodology, resources, formal analysis. Yanting Xie: software, visualization. Hanyu He: data curation, resources. Da Xiong: investigation, data curation. Guo Tian: visualization, investigation. Tao Yang: resources. Junfeng Huang: visualization. Yong Ao: resources. Yue Sun: formal analysis. Weiqing Yang: funding acquisition. Weili Deng: validation, formal analysis, supervision, project administration.

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CONFLICT OF INTEREST
The authors declare no conflict of interest.

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REFERENCES
1. A. Abramson, C. T. Chan, Y. Khan, A. Mermin-Bunnell, N. Matsushita, R. Fong, R. Shad, W. Hiesinger, P. Mallick, S. S. Gambhir, Sci. Adv. 2022, 8, eabn6550.
2. Y. Zhou, C. Wan, Y. Yang, H. Yang, S. Wang, Z. Dai, K. Ji, H. Jiang, X. Chen, Y. Long, Adv. Funct. Mater. 2019, 29, 1806220.
3. S. S. Kwak, S. Yoo, R. Avila, H. U. Chung, H. Jeong, C. Liu, J. L. Vogl, J. Kim, H.-J. Yoon, Y. Park, H. Ryu, G. Lee, J. Kim, J. Koo, Y. S. Oh, S. Kim, S. Xu, Z. Zhao, Z. Xie, Y. Huang, J. A. Rogers, Adv. Mater. 2021, 33, 2103974.
4. G. Tian, W. Deng, D. Xiong, T. Yang, B. Zhang, X. Ren, B. Lan, S. Zhong, L. Jin, H. Zhang, L. Deng, W. Yang, Cell Rep. Phys. Sci. 2022, 3, 100814.
5. Y. Liu, C. Yiu, Z. Song, Y. Huang, K. Yao, T. Wong, J. Zhou, L. Zhao, X. Huang, S. K. Nejad, M. Wu, D. Li, J. He, X. Guo, J. Yu, X. Feng, Z. Xie, X. Yu, Sci. Adv. 2022, 8, eabf6700.
6. J. He, Z. Xie, K. Yao, D. Li, Y. Liu, Z. Gao, W. Lu, L. Chang, X. Yu, Nano Energy 2021, 81, 105590.
7. W. Deng, Y. Zhou, A. Libanori, G. Chen, W. Yang, J. Chen, Chem. Soc. Rev. 2022, 51, 3380.
8. D. Lei, N. Liu, T. Su, Q. Zhang, L. Wang, Z. Ren, Y. Gao, Adv. Mater. 2022, 34, 2106008.
9. Y. Zhou, H. Lian, Z. Li, L. Yin, Q. Ji, K. Li, F. Qi, Y. Huang, VIEW 2022, 3, 20220025.
10. M. Zhu, Y. Yue, Y. Cheng, Y. Zhang, J. Su, F. Long, X. Jiang, Y. Ma, Y. Gao, Adv. Electron. Mater. 2020, 6, 1901064.
11. X. Shi, X. Fan, Y. Zhu, Y. Liu, P. Wu, R. Jiang, B. Wu, H.-A. Wu, H. Zheng, J. Wang, X. Ji, Y. Chen, J. Liang, Nat. Commun. 2022, 13, 1119.
12. C. Ma, D. Xu, Y.-C. Huang, P. Wang, J. Huang, J. Zhou, W. Liu, S.-T. Li, Y. Huang, X. Duan, ACS Nano 2020, 14, 12866.
13. S. Wang, W. Deng, T. Yang, G. Tian, D. Xiong, X. Xiao, H. Zhang, Y. Sun, Y. Ao, J. Huang, J. Chen, W. Yang, Nano Res. 2022, DOI: s12274-022-5014-y.
14. T. Yang, W. Deng, X. Chu, X. Wang, Y. Hu, X. Fan, J. Song, Y. Gao, B. Zhang, G. Tian, D. Xiong, S. Zhong, L. Tang, Y. Hu, W. Yang, ACS Nano 2021, 15, 11555.
15. B. Lan, X. Xiao, A. D. Carlo, W. Deng, T. Yang, L. Jin, G. Tian, Y. Ao, W. Yang, J. Chen, Adv. Funct. Mater. 2022, 32, 2207393.
16. X. Wei, H. Li, W. Yue, S. Gao, Z. Chen, Y. Li, G. Shen, Matter 2022, 5, 1481.
17. Y. Ma, Y. Yue, H. Zhang, F. Cheng, W. Zhao, J. Rao, S. Luo, J. Wang, X. Jiang, Z. Liu, N. Liu, Y. Gao, ACS Nano 2018, 12, 3209.
18. Y. Zhang, J. Yang, X. Hou, G. Li, L. Wang, N. Bai, M. Cai, L. Zhao, Y. Wang, J. Zhang, K. Chen, X. Wu, C. Yang, Y. Dai, Z. Zhang, C. F. Guo, Nat. Commun. 2022, 13, 1317.
19. Y. Cheng, Y. Ma, L. Li, M. Zhu, Y. Yue, W. Liu, L. Wang, S. Jia, C. Li, T. Qi, J. Yang, W. Gao, ACS Nano 2020, 14, 2145.
20. Y. Gao, C. Yan, H. Huang, T. Yang, G. Tian, D. Xiong, N. Chen, X. Chu, S. Zhong, W. Deng, Y. Fang, W. Yang, Adv. Funct. Mater. 2020, 30, 190603.
21. M. Zhong, L. Zhang, X. Liu, Y. Zhou, M. Zhang, Y. Wang, L. Yang, D. Wei, Chem. Eng. J. 2021, 412, 126649.
22. H. Jin, M. O. G. Nayeem, S. Lee, N. Matsuhisa, D. Inoue, T. Yokota, D. Hashizume, T. Someya, ACS Nano 2019, 13, 7905.
23. H. Wang, R. Zhou, D. Li, L. Zhang, G. Ren, L. Wang, J. Liu, D. Wang, Z. Tang, G. Lu, G. Sun, H.-D. Yu, W. Huang, ACS Nano 2021, 15, 9690.
24. D. Zhao, Y. Zhu, W. Cheng, W. Chen, Y. Wu, H. Yu, Adv. Mater. 2021, 33, 2000619.
25. T. Yang, H. Pan, G. Tian, B. Zhang, D. Xiong, Y. Gao, C. Yan, X. Chu, N. Chen, S. Zhong, L. Zhang, W. Deng, W. Yang, Nano Energy 2020, 72, 104706.
26. J. Huang, D. Li, M. Zhao, H. Ke, A. Mensah, P. Lv, X. Tian, Q. Wei, Chem. Eng. J. 2019, 373, 1357.
27. Y. Ma, N. Liu, L. Li, X. Hu, Z. Zou, J. Wang, S. Luo, Y. Gao, Nat. Commun. 2017, 8, 1207.
28. J. Zhang, N. Kong, S. Uzun, A. Levitt, S. Seyedin, P. A. Lynch, S. Qin, M. Han, W. Yang, J. Liu, X. Wang, Y. Gogotsi, J. M. Razal, Adv. Mater. 2020, 32, 2001093.
29. M. Alhabe, K. Maleski, B. Anasori, P. Lelyukh, L. Clark, S. Sin, Y. Gogotsi, Chem. Mater. 2017, 29, 7633.
30. B. Lyu, M. Kim, H. Jing, J. Kang, C. Qian, S. Lee, J. H. Cho, ACS Nano 2019, 13, 11392.
31. H. Huang, X. Chu, Y. Xie, B. Zhang, Z. Wang, Z. Duan, N. Chen, Z. Xu, H. Zhang, W. Yang, ACS Nano 2022, 16, 3776.
32. Y. Xie, H. Zhang, H. Huang, Z. Wang, Z. Xu, H. Zhao, Y. Wang, N. Chen, W. Yang, Nano Energy 2020, 74, 104928.
33. X. Jin, L. Li, S. Zhao, X. Li, K. Jiang, L. Wang, G. Shen, ACS Nano 2021, 15, 18385.
34. Y. Shao, L. Wei, X. Wu, C. Jiang, Y. Yao, B. Peng, H. Chen, J. Huangfu, Y. Ying, C. J. Zhang, J. Ping, Nat. Commun. 2022, 13, 3223.
35. G.-Y. Gou, X.-S. Li, J.-M. Jian, H. Tian, F. Wu, J. Ren, X.-S. Geng, J.-D. Xu, Y.-C. Qiao, Z.-Y. Yan, G. Dun, C. W. Ahn, Y. Yang, T.-L. Ren, Sci. Adv. 2022, 8, eabn2156.
36. X.-F. Zhao, C.-Z. Hang, H.-L. Lu, K. Xu, H. Zhang, F. Yang, R.-G. Ma, J.-C. Wang, D. W. Zhang, Nano Energy 2020, 68, 104346.
37. J. Ma, K. Yang, Y. Jiang, L. Shen, H. Ma, Z. Cui, Y. Du, J. Lin, J. Liu, N. Zhu, Cell Rep. Phys. Sci. 2022, 3, 100908.
38. X. Fu, L. Wang, L. Zhao, Z. Yuan, Y. Zhang, D. Wang, D. Wang, J. Li, D. Li, V. Shulga, G. Shen, W. Han, Adv. Funct. Mater. 2021, 31, 2010533.
39. T. Su, N. Liu, D. Lei, L. Wang, Z. Ren, Q. Zhang, J. Su, Z. Zhang, Y. Gao, ACS Nano 2022, 16, 8461.

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