

Cite this: *Chem. Sci.*, 2024, 15, 9591

All publication charges for this article have been paid for by the Royal Society of Chemistry

# Cross-linked $K_{0.5}MnO_2$ nanoflower composites for high rate and low overpotential Li–CO<sub>2</sub> batteries†

Jiawei Wu,<sup>‡ac</sup> Jian Chen,<sup>‡b</sup> Xiaoyang Chen,<sup>b</sup> Yang Liu,<sup>‡ab</sup> Zhe Hu,<sup>‡d</sup> Feijian Lou,<sup>\*a</sup> Shulei Chou<sup>‡e</sup> and Yun Qiao<sup>‡ab</sup>

Rechargeable Li–CO<sub>2</sub> batteries are deemed to be attractive energy storage systems, as they can effectively inhale and fix carbon dioxide and possess an extremely high energy density. Unfortunately, the irreversible decomposition of the insoluble and insulating Li<sub>2</sub>CO<sub>3</sub> results in awful electrochemical performance and inferior energy efficiency of Li–CO<sub>2</sub> batteries. Furthermore, the low energy efficiency will exacerbate the extra waste of resources. Therefore, it is vital to design novel and efficient catalysts to enhance the battery performance. Herein, a facile, one-step strategy is introduced to design cross-linked, ultrathin  $K_{0.5}MnO_2$  nanoflowers combined with CNTs ( $K_{0.5}MnO_2/CNT$ ) as a highly efficient cathode for Li–CO<sub>2</sub> batteries. Impressively, the Li–CO<sub>2</sub> battery based on the  $K_{0.5}MnO_2/CNT$  cathode achieves a low overpotential (1.05 V) and a high average energy efficiency (87.95%) at a current density of 100 mA g<sup>−1</sup>. Additionally, the  $K_{0.5}MnO_2/CNT$  cathode can steadily run for over 100 cycles (overpotential < 1.20 V). Moreover, a low overpotential of 1.47 V can be obtained even at a higher current density of 1000 mA g<sup>−1</sup>, indicating the superior rate performance of  $K_{0.5}MnO_2/CNT$ . This strategy offers new insight and guidance for the development of low-cost and high-performance Li–CO<sub>2</sub> batteries.

Received 18th March 2024

Accepted 14th May 2024

DOI: 10.1039/d4sc01799d

rsc.li/chemical-science

## Introduction

The massive consumption of fossil fuels has led to a surge in carbon dioxide (CO<sub>2</sub>) emissions, which has caused a severe greenhouse effect.<sup>1–3</sup> A straightforward strategy to alleviate this concern is converting CO<sub>2</sub> into renewable energy. Using Li–CO<sub>2</sub> batteries has been considered as one of the most promising approaches for sustainable utilization and reduction of CO<sub>2</sub> to produce electrochemical energy.<sup>4–7</sup> Generally, the electrochemical reaction mechanism of Li–CO<sub>2</sub> batteries is based on the following reaction:  $4Li + 3CO_2 \leftrightarrow 2Li_2CO_3 + C$  ( $E^0 = 2.80$  V versus Li/Li<sup>+</sup>).<sup>8–11</sup> Unfortunately, Li<sub>2</sub>CO<sub>3</sub> as the main discharge product is an insoluble and wide bandgap insulator with thermodynamic stability.<sup>12,13</sup> Consequently, the irreversible decomposition of Li<sub>2</sub>CO<sub>3</sub> will lead to large polarization, inferior

cycle stability, low energy efficiency, and even battery failure, which are the dominant obstacles in the development of high-performance Li–CO<sub>2</sub> batteries.<sup>14–17</sup> In this regard, exploration and fabrication of effective catalysts is a great choice to improve the CO<sub>2</sub> reduction and evolution reaction.

To date, many efforts have been taken to design efficient catalysts with high catalytic activity. Noble metals, such as Ru, Ir and their oxides, have been demonstrated to enable the reversible formation and decomposition of carbonate at low overpotential, and thus can enhance the energy efficiency of Li–CO<sub>2</sub> batteries,<sup>18–21</sup> whereas, their large-scale application in Li–CO<sub>2</sub> batteries is still limited by the high cost and scarcity of noble metals. Notably, transition metal oxides are regarded as attractive candidates. Recently, Wang and co-workers demonstrated a Mn based metal organic framework with catalytic metal centers and porous structure, which can facilitate the complete and efficient decomposition of the nanostructured Li<sub>2</sub>CO<sub>3</sub> as well as reducing the charge overpotential.<sup>22</sup> Thus, introducing low-cost Mn as catalytic metal centers is a promising approach to decompose the discharge product of Li<sub>2</sub>CO<sub>3</sub>.

In particular, MnO<sub>2</sub> materials have emerged as catalysts, which may enhance the reaction dynamics and reduce the overpotentials for Li–CO<sub>2</sub> batteries. Ge *et al.* first introduced Co-Interstitial  $\alpha$ -MnO<sub>2</sub> nanowires as a cathode for Li–CO<sub>2</sub> batteries, which can deliver a good capacity of 8160 mA h g<sup>−1</sup> at 100 mA g<sup>−1</sup>, high efficiency and high energy density.<sup>23</sup> Meanwhile, IrO<sub>2</sub>-decorated few-layered  $\delta$ -MnO<sub>2</sub> was obtained, in which the IrO<sub>2</sub> acts as catalytically active centers for CO<sub>2</sub>

<sup>a</sup>School of Chemistry and Chemical Engineering, Henan Normal University, Xinxiang, Henan 453007, China. E-mail: liuy986@htu.edu.cn; loufeijian@htu.edu.cn

<sup>b</sup>School of Environment and Chemical Engineering, Shanghai University, Shanghai 200444, China. E-mail: yunqiao@shu.edu.cn

<sup>c</sup>Sinopec Petroleum Engineering Zhongyuan Co. Ltd, Natural Gas Technology Center, Zhengzhou, Henan 450000, China

<sup>d</sup>College of Materials Science and Engineering, Shenzhen University, Shenzhen 518055, China

<sup>e</sup>Institute for Carbon Neutralization, College of Chemistry and Materials Engineering, Wenzhou University, Wenzhou, Zhejiang 325035, China

† Electronic supplementary information (ESI) available. See DOI: <https://doi.org/10.1039/d4sc01799d>

‡ J. Wu and J. Chen contributed equally to this work.

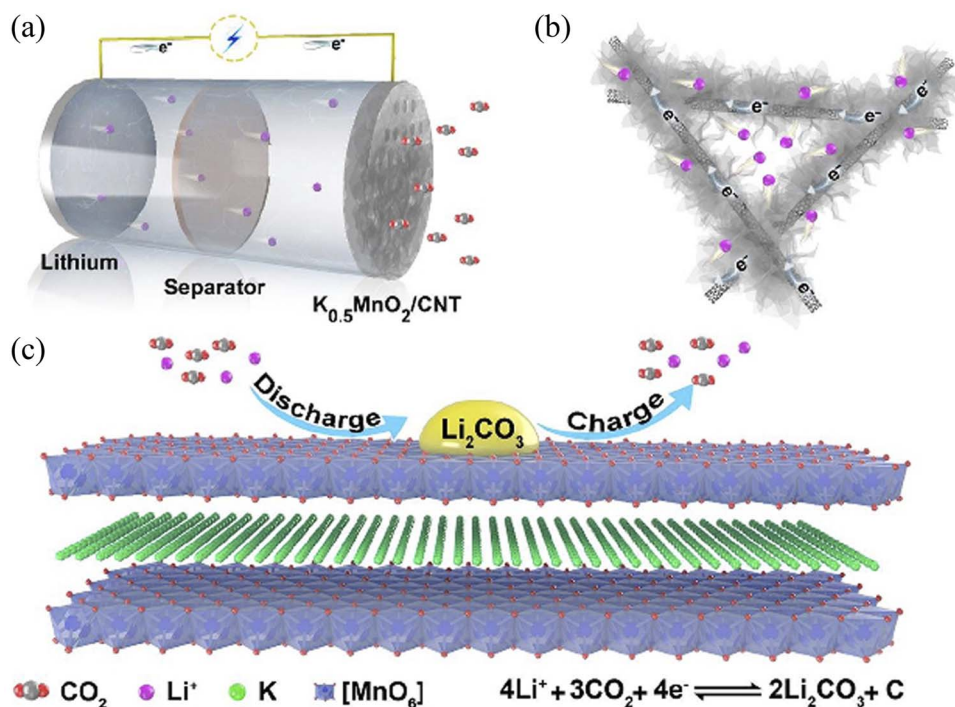


Fig. 1 (a) Schematic diagram of the Li-CO<sub>2</sub> battery with the K<sub>0.5</sub>MnO<sub>2</sub>/CNT cathode. (b) The microstructure of K<sub>0.5</sub>MnO<sub>2</sub>/CNT and (c) the catalytic mechanism of K<sub>0.5</sub>MnO<sub>2</sub>.

reduction, and  $\delta$ -MnO<sub>2</sub> has a co-catalytic effect for conformal growth of amorphous Li<sub>2</sub>CO<sub>3</sub>.<sup>24</sup> However, the electrocatalytic performances are still finite for MnO<sub>2</sub> materials as catalytic electrodes in Li-CO<sub>2</sub> batteries. It is commonly recognized that birnessite MnO<sub>2</sub> exhibits the best activity among various MnO<sub>2</sub>, while studies on layered MnO<sub>2</sub> as a catalyst in Li-CO<sub>2</sub> batteries are still in their infancy stage.<sup>25–27</sup> Therefore, it is imperative to develop K-birnessite MnO<sub>2</sub> as a feasible catalyst for Li-CO<sub>2</sub> batteries with high performance, taking advantage of the catalytic manganese centers and large interlayer space.

Herein, we adopted a facile method to synthesize ultrathin K<sub>0.5</sub>MnO<sub>2</sub> nanoflowers combined with CNTs (K<sub>0.5</sub>MnO<sub>2</sub>/CNT) *via* a hydrothermal process. As a cathode for Li-CO<sub>2</sub> batteries, the K<sub>0.5</sub>MnO<sub>2</sub>/CNT electrode exhibits a low overpotential (1.05 V), high average energy efficiency (87.95%) and excellent rate performance (up to 1000 mA g<sup>-1</sup>). Meanwhile, the cathode can be steadily operated for 100 cycles and the terminal discharge and charge voltages are preserved between 2.72 and 3.92 V. This superb electrochemical performance is ascribed to the outstanding catalytic activity of K<sub>0.5</sub>MnO<sub>2</sub>/CNT. Fig. 1 displays the schematic diagram of the typical Li-CO<sub>2</sub> battery with microstructural K<sub>0.5</sub>MnO<sub>2</sub>/CNT as a cathode, and the corresponding catalytic reactions for CO<sub>2</sub> reduction and evolution. Of note, the introduction of CNTs can not only improve the electronic conductivity of the composite, but also facilitate the formation of ultrathin K<sub>0.5</sub>MnO<sub>2</sub> nanoflowers with small size and high separation. Simultaneously, the cross-linked ultrathin K<sub>0.5</sub>MnO<sub>2</sub> nanoflowers can effectively shorten the electron/Li<sup>+</sup> transport distances, and also expose ample catalytic active sites. Furthermore, K<sup>+</sup> occupies the interlayer space of K<sub>0.5</sub>MnO<sub>2</sub>,

which can not only achieve support and charge balance, but also significantly improve the conductivity and the diffusion rate of Li<sup>+</sup>. Therefore, K<sub>0.5</sub>MnO<sub>2</sub>/CNT can be used as a highly efficient cathode for Li-CO<sub>2</sub> batteries, which is helpful for the realization of ultra-low overpotential, ultra-high energy efficiency, and excellent cycling performance of Li-CO<sub>2</sub> batteries.

## Results and discussion

The morphology and microstructure were first characterized through field emission scanning electron microscopy (FE-SEM). Pristine CNTs with an average diameter of about 20–30 nm (Fig. S1†) were first treated with mixed acid, and then the K<sub>0.5</sub>MnO<sub>2</sub>/CNT composite was achieved *via* a facile, one-step hydrothermal process. The X-ray diffraction (XRD) patterns of the sample are presented in Fig. S2.† In which, the distinct peaks at 12.5°, 25.2°, 37.3°, and 65.6° in the K<sub>0.5</sub>MnO<sub>2</sub>/CNT composite can be well indexed to the (001), (002), ( $\bar{1}11$ ) and (020) planes for monoclinic potassium birnessite (JCPDS No. 80-1098). As shown in Fig. 2a, K<sub>0.5</sub>MnO<sub>2</sub> nanoflowers with diameters of ~200 nm are assembled by ultrathin nanosheets and cover the surface of CNTs, which are cross-linked with each other to form a network void structure. It is of note that the intrinsic voids in the K<sub>0.5</sub>MnO<sub>2</sub>/CNT composite with an interconnected network structure can expose more active sites and provide sufficient space for the discharge deposition. The typical transmission electron microscopy image in Fig. 2b clearly discloses that K<sub>0.5</sub>MnO<sub>2</sub> nanoflowers are composed of interconnected nanoflakes alongside CNTs, which can conventionally increase the electronic conductivity of the



composite. The high-resolution transmission electron microscopy (HRTEM) image shows that the thickness of the nanosheets ranges from 2.70 to 3.30 nm (Fig. 2c), which is coincident with 4–5 layers of  $\text{MnO}_2$  in the (001) direction with an interplanar spacing of  $\sim 0.67$  nm. Moreover, the layered structure is further proved by the high-angle-annular dark-field scanning transmission electron microscopy (HAADF-STEM) image in Fig. 2d. The edge-shared  $[\text{MnO}_6]$  octahedral (bluish violet dots) and K ions (green dots) are alternately distributed between the interlayers, which correspond to 2D layered  $\text{MnO}_2$  in the inset of Fig. 2d.<sup>28,29</sup> Two diffraction rings are observed in selected area electron diffraction (SAED) patterns, which can be indexed to the (111) and (020) planes of  $\text{K}_{0.5}\text{MnO}_2$  (Fig. 2e). As shown in Fig. 2f, Mn, O, C, and K elements are detected in energy-dispersive X-ray spectra (EDS) of  $\text{K}_{0.5}\text{MnO}_2/\text{CNT}$ , further confirming the existence of K ions. Moreover, HAADF-STEM mapping images in Fig. 2g–j clearly reveal that K, Mn, and O elements are homogeneously distributed in layered  $\text{MnO}_2$  nanoflowers. The presence of  $\text{K}^+$  can not only improve the structural stability and charge balance of  $\text{K}_{0.5}\text{MnO}_2$ , but also boost the catalytic activity of the electrode.<sup>30</sup> The existence of carbon further confirms that  $\text{K}_{0.5}\text{MnO}_2$  nanoflowers cover the CNTs substrate (Fig. 2k).

Inductively coupled plasma (ICP) analysis was used to investigate the chemical composition of  $\text{K}_{0.5}\text{MnO}_2/\text{CNT}$ , where the K/Mn molar ratio in  $\text{K}_{0.5}\text{MnO}_2/\text{CNT}$  is about 0.5/1.0 (Table S1†).

Therefore, the molecular formula of  $\text{K}_{0.5}\text{MnO}_2/\text{CNT}$  can be identified as  $\text{K}_{0.5}\text{MnO}_2$ . The thermogravimetric result reveals that the proportion of CNTs in the  $\text{K}_{0.5}\text{MnO}_2/\text{CNT}$  composite is 16.0% (Fig. S3†). The full X-ray photoelectron spectrum (XPS) of  $\text{K}_{0.5}\text{MnO}_2/\text{CNT}$  shows distinct characteristic peaks of K, Mn, O and C elements, further indicating the presence of  $\text{K}_{0.5}\text{MnO}_2$  and CNTs (Fig. S4†). In Fig. S5a,† the high-resolution C 1s XPS spectrum can be deconvoluted into three peaks centered at 284.7, 285.5 and 286.8 eV, which can be ascribed to non-oxygenated ring carbon (C–C), C–N and the C–O bonds, respectively.<sup>31–33</sup> Fig. S5b† shows the high-resolution XPS spectrum of Mn 2p; the two peaks at 654.2 and 642.4 eV correspond to the binding energy of Mn 2p<sub>1/2</sub> and Mn 2p<sub>3/2</sub> for  $\text{K}_{0.5}\text{MnO}_2$ , respectively. Their spin-energy separation is 11.8 eV, consistent with a previous report.<sup>27</sup> Furthermore, the spectrum of Mn 2p can be resolved into three peaks, confirming the existence of a mixed-valence state of  $\text{Mn}^{4+}$  (642.5 eV) and  $\text{Mn}^{3+}$  (644.9 and 654.1 eV) ions in the  $\text{MnO}_6$  subunits.<sup>34,35</sup> The high-resolution XPS spectra of Mn 3s exhibit a splitting of the doublet, because of the parallel spin coupling of 3s and 3d electrons during the photoelectron ejection (Fig. S5c†).<sup>36,37</sup> The energy difference of 4.7 V among the two peaks is attributed to the existence of  $\text{Mn}^{4+}$ . These mixed-valence states of Mn could enhance the catalytic performance of  $\text{MnO}_2$  with different oxide species. As shown in Fig. S5d,† the O 1s spectra display three fitted peaks at 529.9, 531.5 and 532.8 eV, which are assigned to the Mn–O–Mn, Mn–O–H, and H–

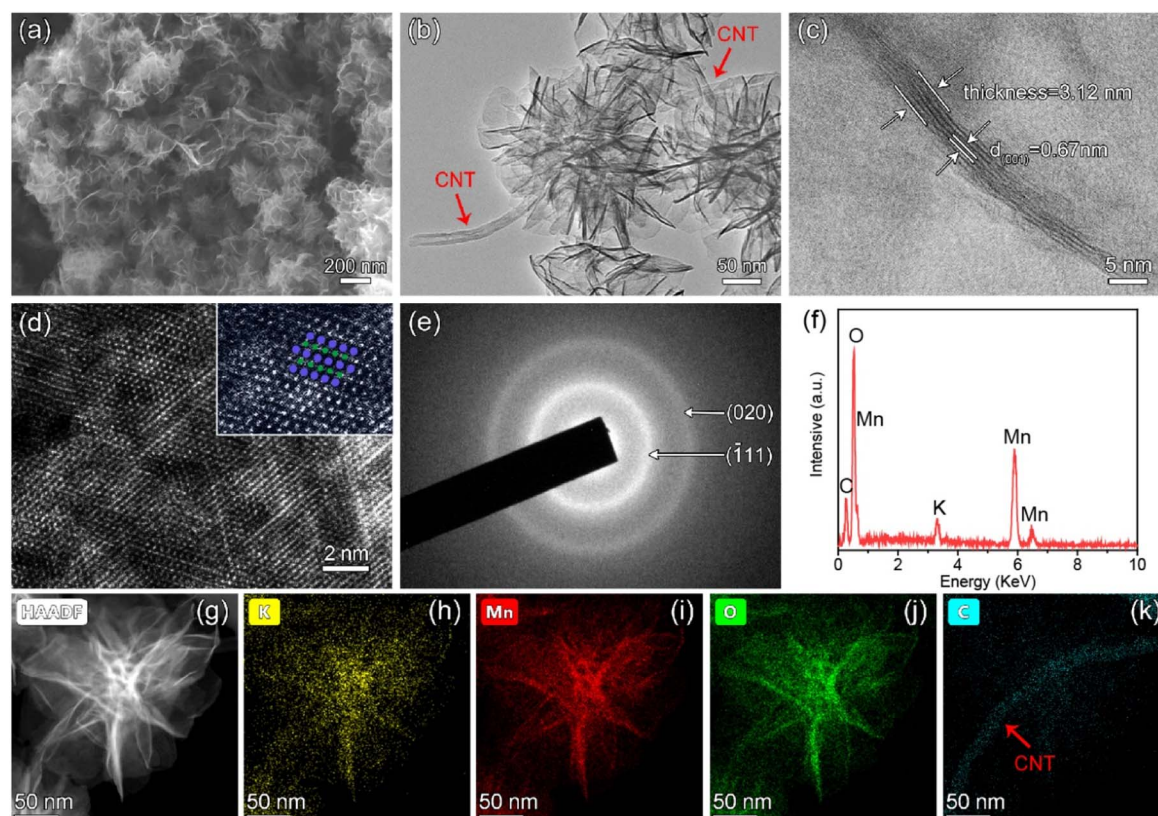


Fig. 2 (a) SEM, (b) TEM, (c) HRTEM, and (d) high-magnification HAADF-STEM images of  $\text{K}_{0.5}\text{MnO}_2/\text{CNT}$  (inset of Fig. 2d: bluish violet dots stand for  $[\text{MnO}_6]$  and green dots represent  $\text{K}^+$ ). (e) SAED patterns and (f) EDS spectrum of  $\text{K}_{0.5}\text{MnO}_2/\text{CNT}$ . (g–k) HAADF-STEM image and the corresponding EDS elemental mapping results of  $\text{K}_{0.5}\text{MnO}_2/\text{CNT}$ .



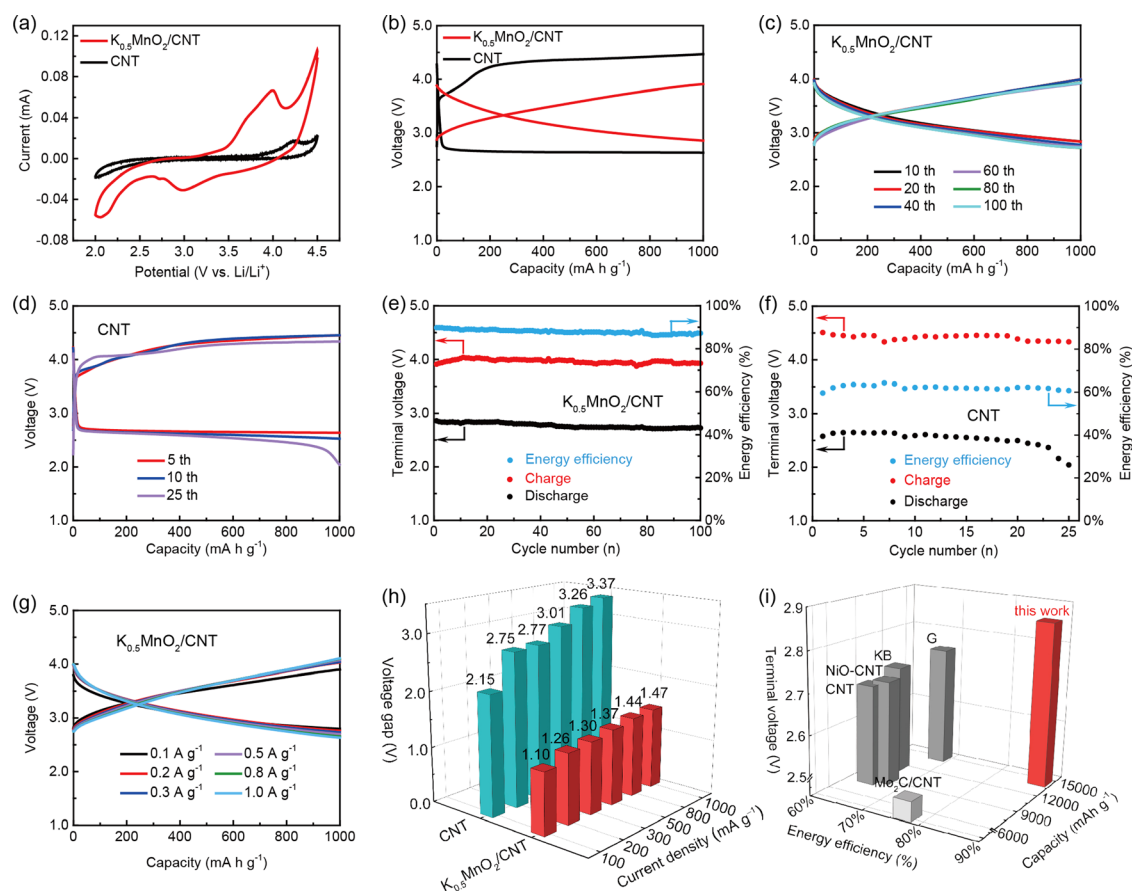


O–H (adsorbed water) bonds, respectively.<sup>38</sup> These results prove the successful synthesis of K-birnessite-type  $\text{MnO}_2/\text{CNT}$ .

To evaluate the electrochemical behavior of the  $\text{K}_{0.5}\text{MnO}_2/\text{CNT}$  cathode in Li– $\text{CO}_2$  batteries, the cyclic voltammetry (CV) measurement was first carried out between 2.0 and 4.5 V at a scan rate of  $0.2 \text{ mV s}^{-1}$ . As shown in Fig. 3a, the  $\text{K}_{0.5}\text{MnO}_2/\text{CNT}$  cathode displays an obvious cathodic peak at 2.98 V, indicating the  $\text{CO}_2$  reduction reaction. In contrast, none of the significant peaks are found for the CNT cathode. Upon the anodic scan, the  $\text{K}_{0.5}\text{MnO}_2/\text{CNT}$  cathode exhibits a significantly lower onset potential ( $\approx 3.0 \text{ V}$ ) than that of the CNT cathode ( $\approx 3.4 \text{ V}$ ). The stronger oxidation peak at 3.95 V for the  $\text{K}_{0.5}\text{MnO}_2/\text{CNT}$  cathode can be ascribed to the  $\text{CO}_2$  evolution reaction ( $\text{CO}_2\text{ER}$ ) with high activity, implying the remarkably boosted kinetic reaction of  $\text{Li}_2\text{CO}_3$  decomposition,  $\text{Li}^+$  and  $\text{CO}_2$  transport. Of note, the  $\text{K}_{0.5}\text{MnO}_2/\text{CNT}$  cathode also endows the larger integral area and higher peak intensity in the CV curves than that of the CNT cathode, suggesting that the synergistic effect between  $\text{K}_{0.5}\text{MnO}_2$  and CNTs significantly improves the catalytic activity of the  $\text{CO}_2$  reduction reaction ( $\text{CO}_2\text{RR}$ ) and  $\text{CO}_2\text{ER}$ . Subsequently, deep discharge/charge tests of Li– $\text{CO}_2$

cells with  $\text{K}_{0.5}\text{MnO}_2/\text{CNT}$  and CNTs as cathodes were also carried out at  $100 \text{ mA g}^{-1}$  between 2.0 and 4.5 V (Fig. S6†). During the discharge process, the CNT cathode delivers a discharge capacity of  $5191 \text{ mA h g}^{-1}$ . It is noteworthy that the  $\text{K}_{0.5}\text{MnO}_2/\text{CNT}$  cathode achieves an increased discharge capacity of  $13\,408 \text{ mA h g}^{-1}$ , which is 2.58 times that of the CNT cathode. Upon the recharge process, the  $\text{K}_{0.5}\text{MnO}_2/\text{CNT}$  cathode delivers a charge capacity of  $14\,267 \text{ mA h g}^{-1}$ , which is significantly higher than that of the CNT cathode ( $3926 \text{ mA h g}^{-1}$ ). The charge capacity is larger than the discharge capacity of the  $\text{K}_{0.5}\text{MnO}_2/\text{CNT}$  cathode, which can be assigned to minor side reactions during the deep charge and discharge processes. On the basis of the above evidence, the  $\text{K}_{0.5}\text{MnO}_2/\text{CNT}$  nanoflowers as a catalyst play a significant role in enhancing the electrocatalytic activity of the cathode.

Fig. 3b shows the first discharge–charge curves of  $\text{K}_{0.5}\text{MnO}_2/\text{CNT}$  and CNT cathodes at  $100 \text{ mA g}^{-1}$  with a capacity limited to  $1000 \text{ mA h g}^{-1}$ . The first discharge and charge terminal voltages are 2.86 and 3.91 V, respectively. The corresponding overpotential is as low as 1.05 V, while the overpotential for the CNT electrode is up to 1.84 V, consistent with the CV results. The



**Fig. 3** The electrochemical performance of the cathodes in Li– $\text{CO}_2$  batteries. (a) CV curves of the  $\text{K}_{0.5}\text{MnO}_2/\text{CNT}$  and CNT electrodes at a scan rate of  $0.2 \text{ mV s}^{-1}$ . (b) The first discharge/charge curves for  $\text{K}_{0.5}\text{MnO}_2/\text{CNT}$  and CNT electrodes at  $0.1 \text{ A g}^{-1}$  with a cut-off capacity of  $1000 \text{ mA h g}^{-1}$ . (c and d) Discharge/charge profiles of (c)  $\text{K}_{0.5}\text{MnO}_2/\text{CNT}$  and (d) CNT cathodes at various cycles at a current density of  $0.1 \text{ A g}^{-1}$ . (e and f) The corresponding terminal discharge/charge voltages and energy efficiencies versus cycle number for (e)  $\text{K}_{0.5}\text{MnO}_2/\text{CNT}$  and (f) CNT cathodes in Li– $\text{CO}_2$  batteries. (g) The charge/discharge profiles of the  $\text{K}_{0.5}\text{MnO}_2/\text{CNT}$  electrode at various current densities. (h) The overpotential comparison of the two cathodes at different current densities. (i) The performance comparison of  $\text{K}_{0.5}\text{MnO}_2/\text{CNT}$  with reported cathodes in terms of energy efficiency, full discharge capacity and terminal voltage.

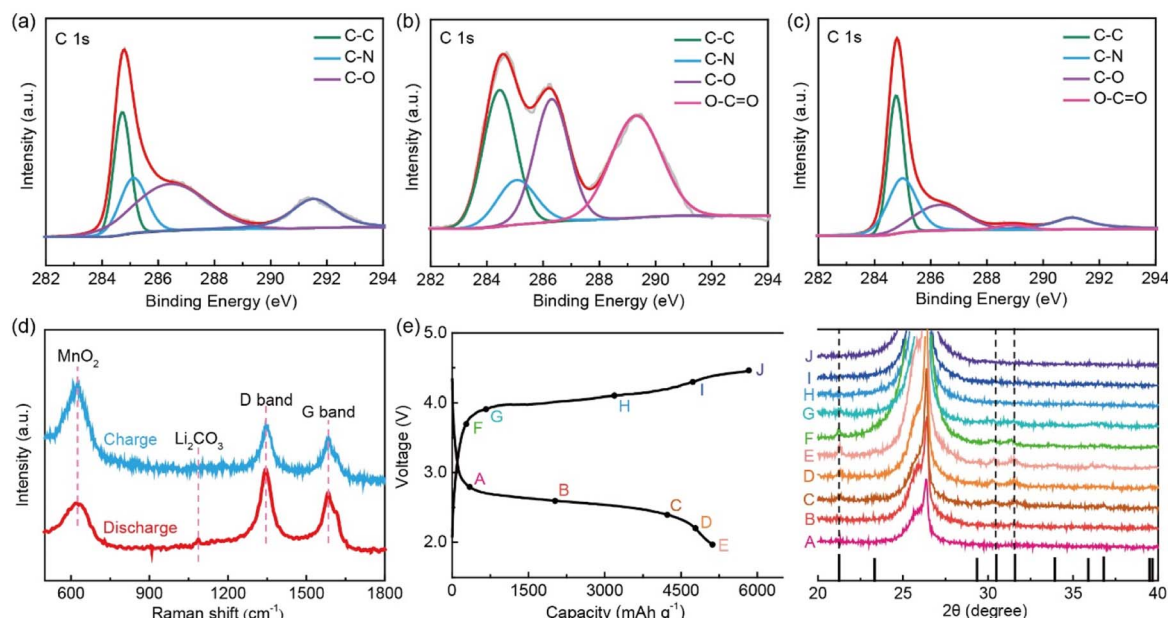


Fig. 4 XPS spectra of C 1s for the  $K_{0.5}MnO_2/CNT$  based cathodes: (a) pristine, (b) discharged, and (c) recharged, respectively. (d) Raman spectra. (e) XRD patterns of the  $K_{0.5}MnO_2/CNT$  cathode at different discharge and charge states (right) and the corresponding discharge/charge curves (left) at  $100\text{ mA g}^{-1}$ .

subsequent discharge/charge profiles at various cycles prove that the  $Li-CO_2$  battery with  $K_{0.5}MnO_2/CNT$  as the cathode can be steadily operated over 100 cycles (Fig. 3c). More importantly, the terminal discharge and charge voltages are maintained between 2.72 and 3.92 V with a minimal overpotential of 1.20 V (Fig. 3e). In contrast, the overpotential for the CNT cathode is up to 1.80 V with an inferior energy efficiency of about 60% and the battery can only run for 25 cycles (Fig. 3d and f).

It is worth mentioning that the average energy efficiency for the  $K_{0.5}MnO_2/CNT$  cathode is as high as 87.95%, which is higher than that of most reported  $Li-CO_2$  batteries (60–80%).<sup>39–43</sup> These results demonstrate that  $K_{0.5}MnO_2/CNT$  as a cathode exhibits an incredible electrochemical performance with low overpotential, high energy efficiency and excellent cycling stability. To the best of our knowledge, the  $K_{0.5}MnO_2/CNT$  cathode delivers the best electrochemical performance among the non-previous catalysts for  $Li-CO_2$  batteries reported to date. Fig. 3g shows the charge/discharge curves of  $Li-CO_2$  batteries with the  $K_{0.5}MnO_2/CNT$  cathode at various current densities. The battery maintains stable discharge and charge plateaus without significant change from 0.1 to  $1.0\text{ A g}^{-1}$ , implying its superior rate performance. The overpotentials of the  $Li-CO_2$  battery based on the  $K_{0.5}MnO_2/CNT$  cathode are 1.10, 1.26, 1.30, 1.37, 1.44, and 1.47 V at current densities of 0.1, 0.2, 0.3, 0.5, 0.8, and  $1.0\text{ A g}^{-1}$ , respectively. It is noteworthy that the terminal discharge and charge voltages are stable at 2.64 and 4.11 V, respectively, even when the current density is up to  $1.0\text{ A g}^{-1}$ , implying its outstanding rate performance. Concurrently, the decomposition of electrolyte and other side reactions can be effectively avoided due to its low terminal charge voltage.<sup>44,45</sup> It can be intuitively observed that the battery with the  $K_{0.5}MnO_2/CNT$  cathode displays much lower overpotentials

than that with CNTs as the cathode at various current densities (Fig. 3h and S7†). The electrochemical impedance spectroscopy (EIS) tests were performed for  $K_{0.5}MnO_2/CNT$  and CNT cathodes after the first discharge and charge processes, as shown in Fig. S8.† It can be seen that the charge transfer resistance ( $R_{ct}$ ) value for  $K_{0.5}MnO_2/CNT$  after charge is smaller than that of the value after discharge, indicating that  $K_{0.5}MnO_2/CNT$  delivers a superior catalytic activity in promoting the decomposition of  $Li_2CO_3$ . Furthermore, the  $K_{0.5}MnO_2/CNT$  cathode also delivers evidently smaller  $R_{ct}$  values than that of CNTs, suggesting that the synergistic effect between  $K_{0.5}MnO_2$  and CNTs can expose ample catalytically active sites, shorten the electron/ $Li^+$  transport distances and facilitate  $Li_2CO_3$  nucleation and decomposition.

In the development of  $Li-CO_2$  batteries, the short cycle life, large overpotential, poor rate performance and inferior energy efficiency are the most urgent and tricky troubles to be solved before commercial application in the future. However, it is also a great challenge to completely solve the above problems. Fortunately, the as-synthesized  $K_{0.5}MnO_2/CNT$  catalyst can substantially overcome those obstacles. For a more intuitive observation, we compare the electrochemical performance of the  $K_{0.5}MnO_2/CNT$  cathode with other current reports (Fig. 3i). Besides, the more systematic and detailed comparison is available in Table S2.† Attractively, the  $Li-CO_2$  battery with the  $K_{0.5}MnO_2/CNT$  cathode presents the overwhelming superiority in the voltage gap, energy efficiency and full discharge capacity. In consequence,  $K_{0.5}MnO_2/CNT$  is a promising candidate to convert  $CO_2$  into electrical energy using aprotic  $Li-CO_2$  batteries.

To further probe the electrochemical reaction process and mechanism upon the charge–discharge processes, *ex situ*

measurements were performed, such as XPS, Raman and XRD. The deconvoluted C 1s spectra for the  $K_{0.5}MnO_2/CNT$  cathode at different stages are shown in Fig. 4a–c. Compared with the original cathode (Fig. 4a), the high-resolution C 1s XPS spectra of the fully discharged cathode exhibit a distinct peak at 289.3 eV related to the O–C=O bond in  $Li_2CO_3$  (Fig. 4b). The peak at 291.2 eV for the pristine cathode is attributed to the C–F bond in the PVDF binder. After the discharge process, the peak disappears, as the nucleation of  $Li_2CO_3$  covers the cathode surface, whereas, a relatively smaller peak at  $\sim 291.0$  eV reappears after the charge process. It is worth noting that the reversible generation and disappearance of  $Li_2CO_3$  after discharge and charge processes indicate that the  $K_{0.5}MnO_2/CNT$  cathode possesses excellent catalytic reversibility and activity (Fig. 4b and c). These results are further verified by Raman spectroscopy, as shown in Fig. 4d. The Raman peak near  $631\text{ cm}^{-1}$  corresponds to the Mn–O bond in the K-birnessite-type  $MnO_2$ , indicating the stability of  $K_{0.5}MnO_2/CNT$  during the cycling process. Additionally, the two main

peaks detected at  $1346$  and  $1586\text{ cm}^{-1}$  are attributed to the D and G bands of the CNT, respectively. Importantly, the characteristic peak at  $1087\text{ cm}^{-1}$  corresponding to  $Li_2CO_3$  emerges after the discharge process, and it disappears after a recharge process. The *ex situ* XRD patterns of the  $K_{0.5}MnO_2/CNT$  electrode at different states were recorded to further reveal the electrochemical reaction process and mechanism (Fig. 4e). The intensity of three additional peaks at  $21.2^\circ$ ,  $30.5^\circ$  and  $31.6^\circ$  is gradually enhanced in the discharge process, which are attributed to the (110), (202) and (002) peaks of  $Li_2CO_3$  (JCPDS No. 09–0359). Subsequently, these peaks disappear after the charge process, indicating the complete decomposition of  $Li_2CO_3$ . These results demonstrate that  $K_{0.5}MnO_2/CNT$  as the cathode is a promising candidate to propel the reversible reduction and evolution of carbon dioxide.

Density functional theory (DFT) calculations have been conducted to reveal the relationship between the structure and performance. The configurations of graphene and graphene/ $MnO_2$  heterostructures are shown in Fig. 5a and b, respectively.

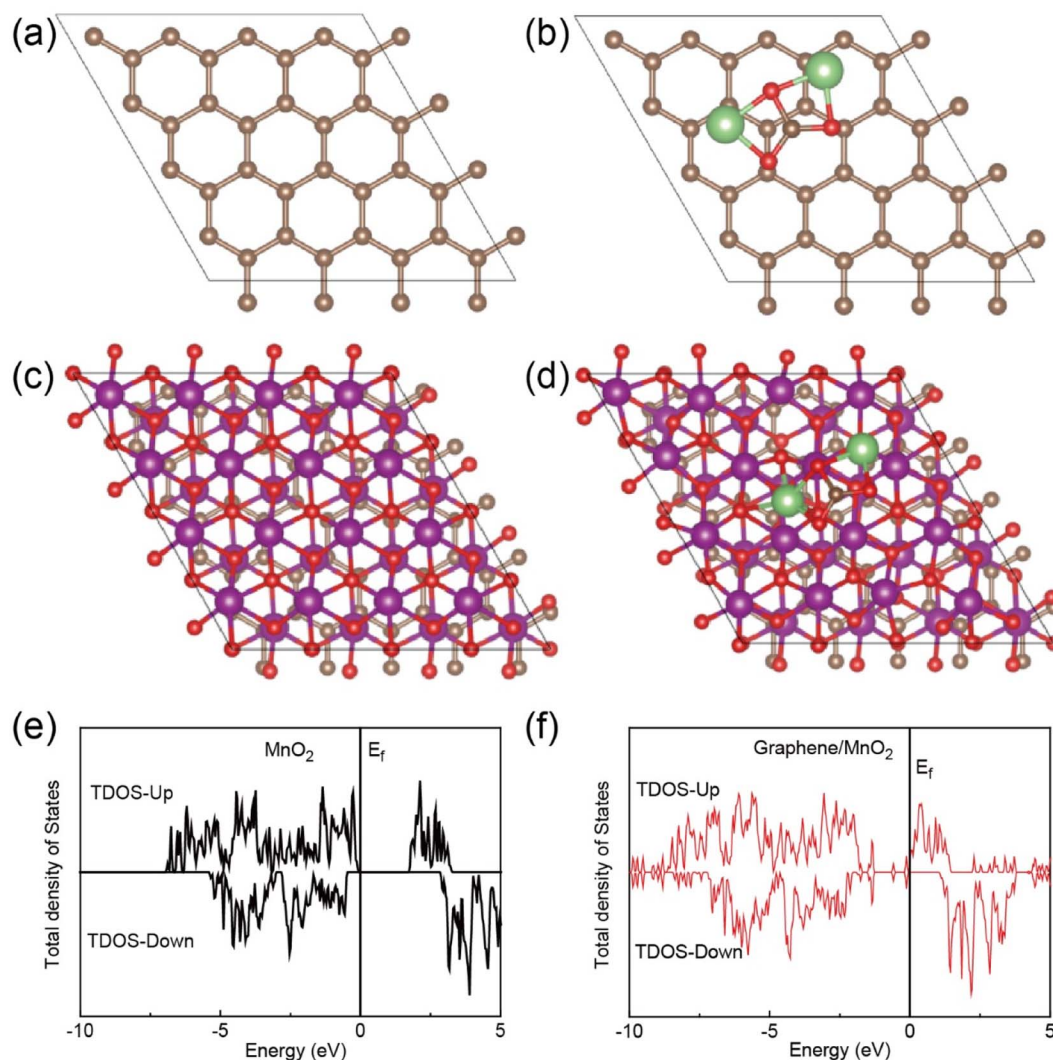


Fig. 5 The configurations of (a) graphene and (b) graphene/ $MnO_2$  heterostructures and the corresponding configurations of  $Li_2CO_3$  adsorption on (c) graphene and (d) graphene/ $MnO_2$  heterostructures. The total density of states for (e)  $MnO_2$  and (f) graphene/ $MnO_2$ .





The capability of  $\text{Li}_2\text{CO}_3$  adsorption was also evaluated. The binding energies with  $\text{Li}_2\text{CO}_3$  are  $-0.15$  eV for the graphene layer (Fig. 5c) and  $-2.65$  eV for the heterostructure (Fig. 5d), indicating the strong interaction between  $\text{Li}_2\text{CO}_3$  and the heterostructure. Moreover, pure  $\text{MnO}_2$  possesses a band gap, and the heterostructure demonstrates no band gap in reverse, indicating improved electrical conductivity according to the density of state results (Fig. 5e and f).

## Conclusions

In summary, we successfully designed a  $\text{K}_{0.5}\text{MnO}_2/\text{CNT}$  composite as a cathode for  $\text{Li}-\text{CO}_2$  batteries. Benefiting from the excellent catalytic activity of  $\text{K}_{0.5}\text{MnO}_2/\text{CNT}$ , the assembled  $\text{Li}-\text{CO}_2$  battery achieves a low overpotential of  $1.05$  V at a current density of  $100$  mA  $\text{g}^{-1}$ . Meanwhile, the  $\text{K}_{0.5}\text{MnO}_2/\text{CNT}$  cathode can be stably operated over 100 cycles in the voltage window of  $2.72-3.92$  V with a high average energy efficiency (87.95%). In addition, the  $\text{K}_{0.5}\text{MnO}_2/\text{CNT}$  cathode still displays a low overpotential of  $1.47$  V even though the current density is increased to  $1.0$  A  $\text{g}^{-1}$ , indicating its superior rate performance for  $\text{CO}_2$  reduction and evolution reactions. This work affords an outstanding strategy for designing cheap and efficient catalysts, and the  $\text{K}_{0.5}\text{MnO}_2/\text{CNT}$  cathode promises to be a promising candidate for further commercial application in  $\text{Li}-\text{CO}_2$  batteries.

## Data availability

Data will be made available on request.

## Author contributions

Y. L., F.-J. L. and Y. Q. proposed the concept and supervised the work; J.-W. W. and J. C. designed the experiments and wrote the paper; Z. H. and S.-L. C. contributed to the discussion and provided suggestions. X.-Y. C. helped to analyze the data. All authors have discussed the results, drafted the manuscript and approved the final version of the manuscript.

## Conflicts of interest

There are no conflicts to declare.

## Acknowledgements

J. Wu and J. Chen contributed equally to this work. This work was supported by the National Natural Science Foundation of China (grant no. U1904187), Natural Science Foundation of Henan for Excellent Young Scholars (no. 202300410223), and the Innovative Research Team of High-Level Local Universities in Shanghai.

## Notes and references

- 1 Y. Yang, S. Louisia, S. Yu, J. Jin, I. Roh, C. Chen, M. V. Fonseca Guzman, J. Feijóo, P.-C. Chen, H. Wang,

- C. J. Pollock, X. Huang, Y.-T. Shao, C. Wang, D. A. Muller, H. D. Abruña and P. Yang, *Nature*, 2023, **614**, 262–269.
- 2 M. T. Dunstan, F. Donat, A. H. Bork, C. P. Grey and C. R. Müller, *Chem. Rev.*, 2021, **121**, 12681–12745.
- 3 S. Ren, D. Joulié, D. Salvatore, K. Torbensen, M. Wang, M. Robert and C. P. Berlinguette, *Science*, 2019, **365**, 367–369.
- 4 L. Fan, H. Shen, D. Ji, Y. Xing, L. Tao, Q. Sun and S. Guo, *Adv. Mater.*, 2022, **34**, e2204134.
- 5 K. Zhang, J. Li, W. Zhai, C. Li, Z. Zhu, X. Kang, M. Liao, L. Ye, T. Kong, C. Wang, Y. Zhao, P. Chen, Y. Gao, B. Wang and H. Peng, *Angew. Chem., Int. Ed.*, 2022, **61**, 2201718.
- 6 B. Chen, D. Wang, J. Tan, Y. Liu, M. Jiao, B. Liu, N. Zhao, X. Zou, G. Zhou and H.-M. Cheng, *J. Am. Chem. Soc.*, 2022, **144**, 3106–3116.
- 7 X. Sun, X. Mu, W. Zheng, L. Wang, S. Yang, C. Sheng, H. Pan, W. Li, C.-H. Li, P. He and H. Zhou, *Nat. Commun.*, 2023, **14**, 536.
- 8 Z. Hu, Y. Xie, D. Yu, Q. Liu, L. Zhou, K. Zhang, P. Li, F. Hu, L. Li, S. Chou and S. Peng, *ACS Nano*, 2021, **15**, 8407–8417.
- 9 F. Ye, L. Gong, Y. Long, S. N. Talapaneni, L. Zhang, Y. Xiao, D. Liu, C. Hu and L. Dai, *Adv. Energy Mater.*, 2021, **11**, 2101390.
- 10 J. Chen, X.-Y. Chen, Y. Liu, Y. Qiao, S.-Y. Guan, L. Li and S.-L. Chou, *Energy Environ. Sci.*, 2023, **16**, 792–829.
- 11 J. Zou, G. Liang, F. Zhang, S. Zhang, K. Davey and Z. Guo, *Adv. Mater.*, 2023, **35**, 2210671.
- 12 Q. Deng, Y. Yang, S. Qu, W. Wang, Y. Zhang, X. Ma, W. Yan and Y. Zhang, *Energy Storage Mater.*, 2021, **42**, 484–492.
- 13 F. Wang, Y. Li, X. Xia, W. Cai, Q. Chen and M. Chen, *Adv. Energy Mater.*, 2021, **11**, 2100667.
- 14 Z. Cheng, Y. Fang, Y. Yang, H. Zhang, Z. Fan, J. Zhang, S. Xiang, B. Chen and Z. Zhang, *Angew. Chem., Int. Ed.*, 2023, **62**, e202311480.
- 15 J. Lin, J. Ding, H. Wang, X. Yang, X. Zheng, Z. Huang, W. Song, J. Ding, X. Han and W. Hu, *Adv. Mater.*, 2022, **32**, 2200559.
- 16 Y. Xu, H. Gong, L. Song, Y. Kong, C. Jiang, H. Xue, P. Li, X. Huang, J. He and T. Wang, *Mater. Today Energy*, 2022, **1**, 100967.
- 17 C. Guo, F. Zhang, X. Han, L. Zhang, Q. Hou, L. Gong, J. Wang, Z. Xia, J. Hao and K. Xie, *Adv. Mater.*, 2023, **35**, 2302325.
- 18 H. Xue, H. Gong, X. Lu, B. Gao, T. Wang, J. He, Y. Yamauchi, T. Sasaki and R. Ma, *Adv. Energy Mater.*, 2021, **11**, 2101630.
- 19 Y. Xing, Y. Yang, D. Li, M. Luo, N. Chen, Y. Ye, J. Qian, L. Li, D. Yang, F. Wu, R. Chen and S. Guo, *Adv. Mater.*, 2018, **30**, 1803124.
- 20 Y. Qiao, S. Xu, Y. Liu, J. Dai, H. Xie, Y. Yao, X. Mu, C. Chen, D. J. Kline, E. M. Hitz, B. Liu, J. Song, P. He, M. R. Zachariah and L. Hu, *Energy Environ. Sci.*, 2019, **12**, 1100–1107.
- 21 Y. Ding, Y. Li and Z.-S. Wu, *Battery Energy*, 2023, **2**, 20220014.
- 22 S. Li, Y. Dong, J. Zhou, Y. Liu, J. Wang, X. Gao, Y. Han, P. Qi and B. Wang, *Energy Environ. Sci.*, 2018, **11**, 1318–1325.
- 23 B. Ge, Y. Sun, J. Guo, X. Yan, C. Fernandez and Q. Peng, *Small*, 2019, **15**, 1902220.
- 24 Y. Mao, C. Tang, Z. Tang, J. Xie, Z. Chen, J. Tu, G. Cao and X. Zhao, *Energy Storage Mater.*, 2019, **18**, 405–413.



- 25 Q. Liu, Z. Hu, L. Li, W. Li, C. Zou, H. Jin, S. Wang and S.-L. Chou, *ACS Appl. Mater. Interfaces*, 2021, **13**, 16585–16593.
- 26 X. Chen, J. Chen, Y. Qiao, Y. Gao, S. Fan, Y. Liu, L. Li, Y. Liu and S. Chou, *Chem. Sci.*, 2024, **15**, 2473–2479.
- 27 X. Chen, J. Chen, Y. Liu, Y. Liu, Y. Gao, S. Fan, X. He, X. Liu, C. Shen, Y. Jiang, L. Li, Y. Qiao and S. Chou, *ACS Appl. Mater. Interfaces*, 2023, **15**, 28106–28115.
- 28 V. B. R. Boppana, S. Yusuf, G. S. Hutchings and F. Jiao, *Adv. Funct. Mater.*, 2013, **23**, 878–884.
- 29 W. Lv, J. Meng, Y. Li, W. Yang, Y. Tian, X. Lyu, C. Duan, X. Ma and Y. Wu, *Nano Energy*, 2022, **98**, 107274.
- 30 Y. Liu, W. Zong, H. Zhou, D. Wang, R. Cao, J. Zhan, L. Liu and B. W.-L. Jang, *Catal. Sci. Technol.*, 2018, **8**, 5344–5358.
- 31 J. Liu, Y. Zhang, L. Zhang, F. Xie, A. Vasileff and S.-Z. Qiao, *Adv. Mater.*, 2019, **31**, 1901261.
- 32 X. Li, J. Zhang, G. Qi, J. Cheng and B. Wang, *Energy Storage Mater.*, 2021, **35**, 148–156.
- 33 K. Lv, D. Wan, R. Pan, W. Suo and Y. Zhu, *Carbon Neutralization*, 2022, **1**, 189–197.
- 34 Y. Liu, Y. Qiao, X. Lou, X. Zhang, W. Zhang and Y. Huang, *ACS Appl. Mater. Interfaces*, 2016, **8**, 14564–14571.
- 35 D. Banerjee and H. W. Nesbitt, *Geochim. Cosmochim. Acta*, 1999, **63**, 3025–3038.
- 36 Y. Liu, Y. Qiao, W. Zhang, H. Wang, K. Chen, H. Zhu, Z. Li and Y. Huang, *J. Mater. Chem. A*, 2015, **3**, 7780–7785.
- 37 Z. Zhuo, K. Dai, R. Qiao, R. Wang, J. Wu, Y. Liu, J. Peng, L. Chen, Y.-d. Chuang, F. Pan, Z.-x. Shen, G. Liu, H. Li, T. P. Devereaux and W. Yang, *Joule*, 2021, **5**, 975–997.
- 38 M. Chigane and M. Ishikawa, *J. Electrochem. Soc.*, 2000, **147**, 2246.
- 39 J. Chen, K. Zou, P. Ding, J. Deng, C. Zha, Y. Hu, X. Zhao, J. Wu, J. Fan and Y. Li, *Adv. Mater.*, 2019, **31**, e1805484.
- 40 P. Tan, Z. H. Wei, W. Shyy, T. S. Zhao and X. B. Zhu, *Energy Environ. Sci.*, 2016, **9**, 1783–1793.
- 41 S. Yang, P. He and H. Zhou, *Energy Environ. Sci.*, 2016, **9**, 1650–1654.
- 42 J. Zhou, X. Li, C. Yang, Y. Li, K. Guo, J. Cheng, D. Yuan, C. Song, J. Lu and B. Wang, *Adv. Mater.*, 2019, **31**, 1804439.
- 43 Y. Li, J. Zhou, T. Zhang, T. Wang, X. Li, Y. Jia, J. Cheng, Q. Guan, E. Liu, H. Peng and B. Wang, *Adv. Funct. Mater.*, 2019, **29**, 1808117.
- 44 T. Jian, W. Ma, C. Xu, H. Liu and J. Wang, *eScience*, 2023, **3**, 100114.
- 45 Z. Wang, B. Liu, X. Yang, C. Zhao, P. Dong, X. Li, Y. Zhang, K. Doyle-Davis, X. Zeng, Y. Zhang and X. Sun, *Adv. Funct. Mater.*, 2023, **33**, 2213931.

