


 Cite this: *RSC Adv.*, 2022, 12, 12997

Nitrogen-doped mesoporous carbon supported CuSb for electroreduction of CO₂†

 Yue Hou,^a Cheng-Jie Jiang,^a Ying Wang,^a Jing-Wei Zhu,^a Jia-Xing Lu^{*ab} and Huan Wang^{*ab}

 Received 24th March 2022
Accepted 25th April 2022

DOI: 10.1039/d2ra01893d

rsc.li/rsc-advances

The construction of an efficient catalyst for electrocatalytic reduction of CO₂ to high value-added fuels has received extensive attention. Herein, nitrogen-doped mesoporous carbon (NMC) was used to support CuSb to prepare a series of materials for electrocatalytic reduction of CO₂ to CH₄. The catalytic activity of the composites was significantly improved compared with that of Cu/NMC. In addition, the Cu content also influenced the activity of electrocatalytic CO₂ reduction reaction. Among the materials used, the CuSb/NMC-2 (Cu: 5.9 wt%, Sb: 0.49 wt%) catalyst exhibited the best performance for electrocatalytic CO₂ reduction, and the faradaic efficiency of CH₄ reached 35%, and the total faradaic efficiency of C1–C2 products reached 67%.

Introduction

The huge combustion of fossil fuels such as coal, oil, and natural gas has led to a significant increase in the content of CO₂ in the atmosphere, causing serious ecological and environmental problems.^{1–3} At the same time, CO₂ is also a rich and widely distributed potential carbon resource. However, CO₂ is a thermodynamically stable molecule, which makes it difficult to be reduced.⁴ Among the various methods of utilization of CO₂, electrochemical method can be carried out at room temperature and atmospheric pressure.⁵ Moreover, CO₂ can be converted into HCOOH, CO, alcohols or hydrocarbon products by different materials. Designing electrocatalysts with high faradaic efficiency (FE) and high stability is still a challenge.

Cu is considered to be an ideal CO₂ reduction electrode material due to its low cost and good catalytic performance compared with precious metals, such as Au⁶ and Pd.⁷ Moreover, Cu is the only metal electrocatalyst that can produce hydrocarbon in electrocatalytic CO₂ reduction reaction (CO₂RR), but its selectivity is poor.⁸ Fortunately, modifying the Cu electrode by adding another metal can stabilize the intermediate and increase the selectivity of catalyst. Lee *et al.* believed that Cu surface-bound CO transfers to the second site may cause hydrogenation or additional C–C coupling.⁹ Therefore, the Cu-based alloy catalyst has attracted widespread attention. Feng *et al.* prepared a homogeneous Cu–Zn alloy catalyst for the electrocatalytic CO₂RR, and a 33.3% FE of ethylene can be

obtained at –1.1 V *vs.* RHE.¹⁰ Su *et al.* synthesized hierarchically macroporous-mesoporous Cu/Zn alloys with two different pore diameters and adjustable alloy compositions. Through the synergistic effect of the hierarchical pore structure and the bimetallic elemental compositions, the electrocatalytic CO₂RR ability was significantly improved. The FE of ethanol reached 46.6% at –0.8 V *vs.* RHE and the catalyst had a stability of up to 11 h.¹¹ These studies show that Cu-based alloy catalyst is an effective catalyst for electrocatalytic CO₂RR with high selectivity.

On the other hand, mesoporous carbon materials have received widespread attention due to their large specific surface area, uniform and adjustable pore structure, stable chemical properties and high electrical conductivity.^{12–15} Incorporating nitrogen into the mesoporous carbon material, due to the existence of nitrogen lone pair electrons, makes the originally neutral carbon material possess Lewis basicity, which is conducive to the adsorption of CO₂. Qin *et al.* used nitrogen-doped porous carbon for electrocatalytic CO₂RR, and a high FE of formate (68%) can be achieved at –0.86 V *vs.* RHE.¹⁶ In addition, nitrogen can also form coordinate bond with metals to improve the stability of the supported catalyst.^{17–19}

Based on these studies, a series of NMC supported CuSb catalysts (CuSb/NMC) for electrocatalytic CO₂RR were tailored and investigated in this work. By preparing materials with different Cu contents, the optimal CuSb/NMC catalyst was explored, and the FE of CH₄ reached 35%.

Results and discussion

CuSb/NMC composites were prepared by impregnation method (Fig. S1†), in which NMC precursor, Cu(NO₃)₂·3H₂O and SbCl₃ ethanol solution were mixed and then calcined at 500 °C under the atmosphere of N₂ (see the Experimental section for detail).

^aShanghai Key Laboratory of Green Chemistry and Chemical Processes, School of Chemistry and Molecular Engineering, East China Normal University, Shanghai, 200062, China. E-mail: jxlu@chem.ecnu.edu.cn; hwang@chem.ecnu.edu.cn

^bInstitute of Eco-Chongming, Shanghai 202162, China

† Electronic supplementary information (ESI) available: XRD, SEM, N₂ adsorption and desorption isotherms, and CVs. See <https://doi.org/10.1039/d2ra01893d>



The information about the morphology of materials can be obtained by scanning electron microscope (SEM) shown in Fig. 1 and S2,[†] and the particle diameter distribution histograms of materials are shown in Fig. S3.[†] The surface of NMC is flat and smooth (Fig. 1a). The surface morphologies of the substrate of CuSb/NMC, Cu/NMC and Sb/NMC catalysts are similar to those of NMC, which indicates that the combination of metals may not change the morphology of NMC. The metal particles of Cu/NMC (Fig. 1b) are clustered together. The interval with the largest particle number distribution of Cu/NMC is 127–161 nm (Fig. S3a[†]). The SEM image of Sb/NMC (Fig. 1c) shows a small number of particles. Compared with Cu/NMC, CuSb/NMC composites have better dispersion and smaller particles (Fig. 1d and S2[†]). The interval with the largest particle number distribution of CuSb/NMC-1, CuSb/NMC-2 and CuSb/NMC-3 is 70–85 nm, 70–85 nm and 85–100 nm, respectively (Fig. S3b–d[†]). According to the results of the particle size analysis, the particles of CuSb/NMC-1 and CuSb/NMC-2 composites possessed the similar size. Besides, due to a higher Cu(NO₃)₂ input, more nanoparticles are observed over the CuSb/NMC-2 (Fig. 1d) compared with those of the CuSb/NMC-1 (Fig. S2a[†]). The particles of CuSb/NMC-3 are larger than those of CuSb/NMC-2 (Fig. S3c and d[†]). It is possible that the increase of its loading leads to the aggregation of particles (Fig. S2b[†]), which might result in the low catalytic activity for CuSb/NMC-3.

X-ray diffraction (XRD) was used to characterize the crystal-line phase structure of the composite materials, as shown in Fig. 2. The XRD pattern of NMC reveals one characteristic peak

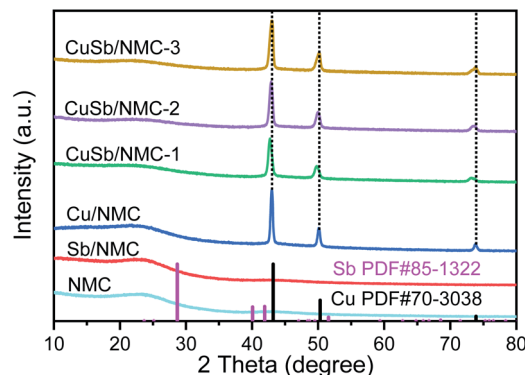


Fig. 2 XRD diffraction patterns of NMC, Cu/NMC, Sb/NMC and CuSb/NMC with different Cu contents.

at $2\theta = 23^\circ$, which is attributed to the amorphous peak of NMC.^{20,21} Cu/NMC have obvious peaks at $2\theta = 43.1^\circ$, 50.2° and 73.8° , which are attributed to the (111), (200) and (220) crystal planes of Cu(0) according to PDF# 70-3038, respectively. It shows that Cu exists in the form of Cu⁰ in Cu/NMC, and there is no Cu oxidation state species. No Sb-related diffraction peaks are detected in the XRD pattern of the Sb/NMC material, which might be due to the low Sb loading. Obvious diffraction peaks of Sb⁰ could be detected with high Sb loading (Fig. S4[†]). The peak positions of CuSb/NMC are close to those of Cu/NMC, and slightly shifted to low angles. And, with the decrease of Cu/Sb ratio, this influence gradually increases. Therefore, it is speculated that Sb is doped into the crystal lattice of Cu to form CuSb alloy.²² So CuSb/NMC is more dispersed than Cu/NMC (Fig. 1b and d).

The actual contents of Cu and Sb measured by inductively coupled plasma atomic emission spectroscopy (ICP-AES) are listed in Table 1. The loadings of Sb in Sb/NMC and CuSb/NMC composites are around 0.5 wt%. The Cu contents of CuSb/NMC-1, CuSb/NMC-2, CuSb/NMC-3 are 2.8 wt%, 5.9 wt% and 8.8 wt%, respectively. The content of Cu in Cu/NMC is 6.1 wt%.

The morphology of CuSb/NMC-2 was further observed by Transmission Electron Microscope (TEM). As it can be seen in Fig. 1e, the metal particles and carbon substrate can be facily observed. Fig. 1f shows the characteristic Cu (111) facet with the lattice fringe of 0.208 nm. Besides, another particle with the lattice fringe of 0.236 nm was also observed, which may be caused by the doping of Sb.

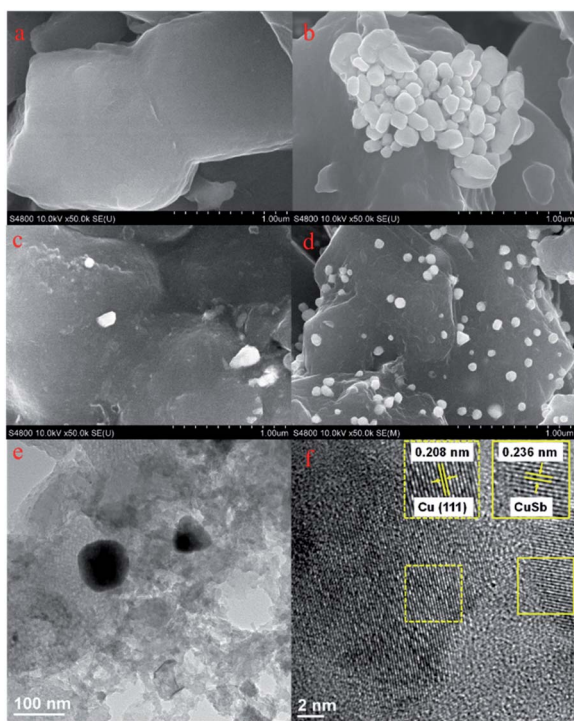


Fig. 1 SEM characterization results of materials (a) NMC, (b) Cu/NMC, (c) Sb/NMC, and (d) CuSb/NMC-2; and (e) TEM as well as (f) HR-TEM images of CuSb/NMC-2.

Table 1 Textural and structural characteristics of composites

Sample	Cu loading ^a (wt%)	Sb loading ^b (wt%)	S_{BET}^c (m ² g ⁻¹)
NMC	—	—	460
Sb/NMC	—	0.51	461
Cu/NMC	6.1	—	433
CuSb/NMC-1	2.8	0.46	454
CuSb/NMC-2	5.9	0.49	432
CuSb/NMC-3	8.8	0.47	406

^a Cu loading obtained by ICP. ^b Sb loading obtained by ICP. ^c S_{BET} Brunauer–Emmett–Teller (BET) surface area.



In order to determine the surface chemical composition of the CuSb/NMC composite, X-ray photoelectron spectroscopy (XPS) analysis was performed on the CuSb/NMC-2 material, and the results are shown in Fig. 3. It can be seen from the full spectrum (Fig. 3a) that there are five elements of C, O, N, Cu and Sb on the composite. Fig. 3b shows the Sb 3d spectrum and O 1s spectrum. The peaks of Sb 3d_{5/2} and Sb 3d_{3/2} (binding energy of 528.1 and 537.2 eV, respectively) clearly show that Sb exists in the form of Sb⁰ in CuSb/NMC.²³ The O 1s at 530.8 eV can be assigned to the oxygen-containing groups in carbon skeleton.²⁴ Fig. 3c is the high-resolution Cu 2p spectrum of the material. There are two obvious characteristic peaks at 933.2 eV and 953.2 eV, which can be attributed to the characteristic Cu 2p_{3/2} and Cu 2p_{1/2}.²⁵ Combined with the XRD characterization results, it shows that the Cu element in the material mainly exists in the form of Cu⁰. It is worth noting that the binding energy (B.E.) of Sb 3d_{5/2} is negatively shifted by 0.2 eV compared with the standard B.E. (528.3 eV), while the B.E. of Cu 2p_{3/2} is shifted to a higher value (933.2 eV) compared to the standard B.E. (933.0 eV). These findings jointly indicate that there is an electronic shift from Cu to Sb, which is possibly originated from the doping of Sb into the Cu lattice. From the N 1s spectrum (Fig. 3d), it can be seen that there are two obvious characteristic peaks near 400.4 eV and 398.5 eV, which can be attributed to pyrrolic N and pyridine N, respectively.²²

N₂ adsorption–desorption measurements were performed to explore the textural characteristics of the materials. It can be seen from Fig. S5a† that all materials show a typical mesoporous structure features–type-IV adsorption isotherm and type-H2 hysteresis loop. Fig. S5b† shows that NMC and composites have narrow pore size distribution of about 5 nm. The corresponding specific surface areas are listed in Table 1. It can be seen from Table 1 that the specific surface area of the pure NMC are 460 m² g⁻¹. The specific surface area of Sb/NMC is not significantly different from that of NMC, which may be due to the low loading of Sb. The specific surface area of Cu/NMC decreases compared with that of NMC, which may be

due to the high specific gravity of Cu.²⁶ For CuSb/NMC composites, with the increase of Cu content, the specific surface area of the material basically shows a downward trend. This phenomenon may be due to the increase of the specific gravity of Cu.

Linear sweep voltammetry (LSV) measurement was used to study the possibility of CuSb/NMC-2 as CO₂RR catalyst and compare the electrocatalytic activities of different materials. As shown in Fig. S6,† the current density under CO₂ atmosphere is higher than that under N₂ atmosphere, indicating that CuSb/NMC-2 is favorable for CO₂RR. The LSV curves of different materials under CO₂ atmosphere are shown in Fig. 4a, it can be seen that the electrochemical behaviors of different materials under CO₂ atmosphere are different. In the range of -0.8 V to -1.6 V vs. RHE, the current density of CuSb/NMC composites are higher than those of Cu/NMC, Sb/NMC and NMC materials, which indicates that the CuSb/NMC composites have higher catalytic activity of CO₂RR than Cu or Sb-supported material and pure NMC. Potentiostatic electrolysis was carried out at -1.46 V vs. RHE to investigate the electrocatalytic reduction ability of different materials, and the results are shown in Fig. 4b. When Sb/NMC and NMC were used as electrode materials, only H₂ was detected in gas products. When Cu/NMC was used as electrode material, CH₄, C₂H₄, CO and H₂ were

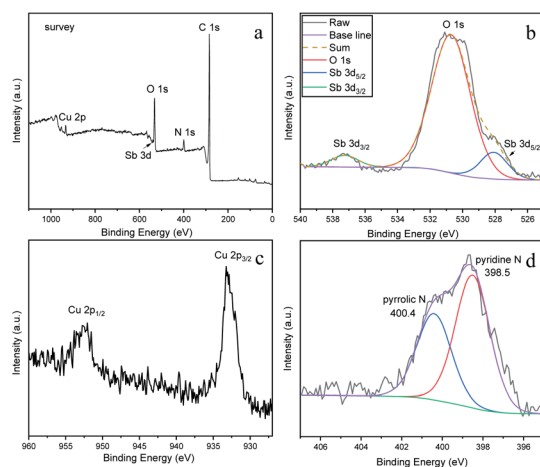


Fig. 3 (a) XPS survey spectrum, (b) Sb 3d spectrum and O 1s spectrum, (c) Cu 2p spectrum and (d) N 1s spectrum of CuSb/NMC-2.

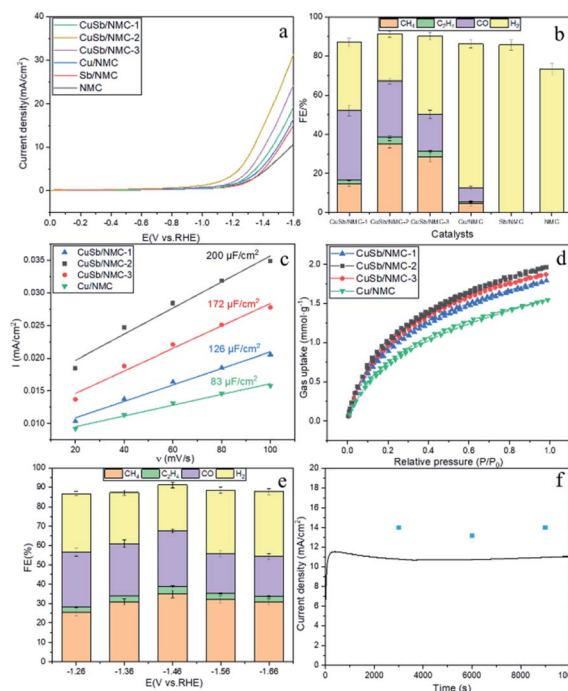


Fig. 4 (a) LSV curves of catalysts on glassy carbon electrode under saturated CO₂; (b) FEs of CO₂ reduction products of catalysts at -1.46 V vs. RHE in 0.1 M KHCO₃ solution saturated with CO₂; (c) the relationship between I and ν in CuSb/NMC composites and Cu/NMC; (d) CO₂ adsorption capacity of CuSb/NMC composites and Cu/NMC; (e) in the 0.1 M KHCO₃ solution, the FEs of CO₂ reduction products of different potentials on the CuSb/NMC-2 catalyst; (f) FE of CH₄ and current density over CuSb/NMC-2 electrode at -1.46 V vs. RHE within 10 000 s.



detected. Adding Cu to NMC for electrocatalytic CO₂RR can generate CH₄, C₂H₄ and CO, which indicating that Cu is the main active site of the CO₂RR. Interestingly, the FE of CH₄ over the CuSb/NMC composites was significantly higher than that over the Cu/NMC. Moreover, the hydrogen evolution reaction on CuSb/NMC composites is better suppressed than that on Cu/NMC. The high CO₂RR catalytic activity of the CuSb/NMC composites may be due to the electron shift from Cu to Sb that changes the electronic structure effect of the composites.

In order to investigate the influence of Cu content over the CuSb/NMC composites, the materials were tested by LSV measurement (Fig. 4a). The current density on CuSb/NMC-2 material was higher than those on the other two different CuSb/NMC materials with different Cu contents, showed obvious catalytic activity of CO₂RR. Moreover, under the potential of -1.46 V vs. RHE, the FE of CH₄ over the composites was greatly affected by the Cu content (Fig. 4b). With the increase of Cu content, the FE of CH₄ first increased and then decreased. The FE of C1–C2 products (CH₄, CO and C₂H₄) also increased first and then decreased. This may be because the addition of Cu affects the number of active sites. As shown by SEM images, too little Cu loading leads to fewer particles and active sites in the CuSb/NMC composite materials, while too much loading results in the aggregation of particles and thus reduces the active sites. Among all the materials, CuSb/NMC-2 exhibited the best catalytic performance for CH₄.

The larger electrochemical active surface area (ECSA), the more catalytically active sites can be provided for the electrocatalytic CO₂RR.²⁷ To check the ECSA of these materials, cyclic voltammograms in N₂-saturated 0.1 M KHCO₃ solution have been performed (Fig. S7†). The linear fitting diagram of the reduction current and the scanning rate of CuSb/NMC composites and Cu/NMC are shown in Fig. 4c. The C_{dl} of CuSb/NMC-1, CuSb/NMC-2, CuSb/NMC-3, Cu/NMC were 126 μF cm⁻², 200 μF cm⁻², 172 μF cm⁻² and 83 μF cm⁻², respectively. The result of electrolysis corresponded to the C_{dl} of composites, which is positively correlated with ECSA. In general, the C_{dl} of CuSb/NMC composites were higher than that of Cu/NMC. It is possible that the particles of the composites are more dispersed due to the incorporation of Sb, which can be seen from the SEM characterization in Fig. 1 and S2,† thus their ECSAs are larger. For CuSb/NMC-1 and CuSb/NMC-2 materials, increasing the Cu content gradually increased the ECSA, which is beneficial to the electrocatalytic reduction of CO₂. The CuSb/NMC-2 had the largest ECSA. Thus, when the CuSb/NMC-2 was used as electrode material, the FE of CH₄ was the highest. When the Cu content continued to increase, the particles started to aggregate, which might result in minimally exposed electroactive sites and decreased the FE of CH₄. This result was also consistent with SEM.

Another important factor to improve the catalytic capacity of CO₂RR is the CO₂ adsorption capacity.^{27–30} Therefore, CO₂ adsorption and desorption tests were performed on the materials (Fig. 4d). CuSb/NMC composites showed a higher adsorption capacity of CO₂ than Cu/NMC. Among a series of materials with different Cu contents, CuSb/NMC-2 had the

highest CO₂ adsorption capacity, which may be beneficial for electrocatalytic CO₂RR.

In order to explore the influence of electrolytic potential, CuSb/NMC-2, the optimal catalyst previously explored, was used as electrode material for CO₂ potentiostatic electrolysis. It can be seen from Fig. 4e that with the negative shift of the potential, the FE of CH₄, C₂H₄ and CO reached the maximum at -1.46 V vs. RHE (35%, 3% and 29%, respectively), and then the FE of CH₄ and CO decreased due to the more intense hydrogen evolution reaction. A suitable negative shift of potential can provide sufficient energy for the reaction, thus facilitating electrocatalytic CO₂RR. Therefore, -1.46 V vs. RHE was the optimal reaction potential. When the potential is too negative, the hydrogen evolution reaction is intense, which is not conducive to the electrocatalytic CO₂RR.

The stability of the optimal material CuSb/NMC-2 was tested by electrolysis at the optimal potential (-1.46 V vs. RHE) for a long time. In the process of electroreduction, the current density shows an upward trend within 300 s and then stabilizes at 11 mA cm⁻² within 10 000 s without obvious change (Fig. 4f). The FE of CH₄ does not change significantly and remains around 35%. The electrolytic material was characterized by SEM and XRD, and the results are shown in Fig. S8.† As can be seen from the SEM diagram of the material in Fig. S8a,† no obvious agglomeration occurred in the material after electrolysis. As can be seen from the XRD characterization of the material in Fig. S8b,† the peak positions of the material before and after electrolysis did not change, indicating that the material has good stability.

Conclusions

In short, we have synthesized a series of materials with different Cu contents for electrocatalytic reduction of CO₂ to CH₄. Compared with Cu/NMC, Sb/NMC and NMC, CuSb/NMC exhibits excellent electrocatalytic performance of CO₂RR. CuSb/NMC-2 has the best catalytic performance, and the FE of CH₄ (35%) is 7 times that of Cu/NMC. The introduction of Sb facilitated the dispersion of particles, inhibited their agglomeration and increased the catalytic active sites.

Experimental

Materials

3-Amino phenol (A.R.), hexamethylene tetramine (A.R.), Cu(NO₃)₂·3H₂O (A.R.), SbCl₃ (A.R.), ethanol (A.R.) and KHCO₃ (A.R.) were purchased from Sinopharm Chemical Reagent Co. Ltd; F127 (Shanghai Aladdin Reagents Co. Ltd); Nafion® 117 solution (5%, Dupont); Nafion 117 membrane (Dupont); Carbon paper (CP, HCP010, Shanghai Hesen Electrical Co. Ltd); CO₂ and N₂ (99.99%, Shanghai Dumaoai Purifying Gas Co. Ltd).

Characterization

XRD patterns were recorded using an Ultima IV X-ray powder diffractometer equipped with Cu K α radiation ($k = 1.5406$ Å). The values for actual Cu and Sb loads of the synthesized



catalysts were determined on an inductively coupled plasma atomic emission spectroscopy (ICP-AES, IRIS Intrepid II XPS, Waltham, MA, USA). XPS analysis was performed on the Thermo Scientific ESCA Lab 250Xi using 200 W monochromatic Al K α radiation. The 500 mm X-ray spot was used. The base pressure in the analysis chamber was about 3×10^{-10} mbar. SEM morphology of the samples was characterized using a Hitachi S4800 scanning electron microscope at 10 kV. TEM images were recorded by TECNAI G2F30 transmission electron microscope. Nitrogen adsorption-desorption isotherms and BET surface areas were measured with a Belsorp-Max analyzer at 77 K. The adsorption isotherms of CO₂ were determined at 25 °C with a Belsorp-Max analyzer. All the electrochemical experiments were performed using a CHI650A electrochemical station (Shanghai Chenhua Instrument Co. Ltd).

Materials synthesis

The NMC precursor was synthesized by the method previously reported in the literature.²² The synthesis procedure of CuSb/NMC is shown in Fig. S1.† Typically, 0.5 g of NMC precursor was dispersed in 25 mL of ethanol. Subsequently, 0.1 g of Cu(NO₃)₂·3H₂O and 4.3 mL of 5 mM SbCl₃ ethanol solution were successively added to the NMC precursor dispersion and stirred for 4 h. After that, the solvent was removed by rotary evaporation at 40 °C. The resulting solid was heated to 500 °C with a rate of 1 °C min⁻¹ and kept at that temperature for 3 h under the atmosphere of N₂. The material obtained after calcination was named as CuSb/NMC-2. By adjusting the amount of Cu(NO₃)₂·3H₂O to 0.08 g and 0.12 g, CuSb/NMC-1 and CuSb/NMC-3 were also prepared. Moreover, Cu/NMC and Sb/NMC were prepared using the same process, except for the absence of SbCl₃ ethanol solution or Cu(NO₃)₂·3H₂O, respectively.

Electrochemical study

In order to prepare the CuSb/NMC electrode, 2 mg of the CuSb/NMC material prepared above was ultrasonically dispersed in 40 μ L of deionized water and 20 μ L of Nafion 117 dispersion (5 wt%) to form a homogeneous solution. The resulting solution was coated on the surface of the carbon paper with a pipette, and then dried at room temperature. The coating amount of catalyst was 0.6 mg cm⁻².

The electrolysis experiment was carried out in an H-type electrolytic cell separated by a Nafion 117 proton exchange membrane at 25 °C with a CuSb/NMC electrode as the cathode, a Pt mesh electrode as the anode and a saturated calomel electrode (SCE) as the reference electrode. A 0.1 M KHCO₃ solution saturated with CO₂ was used as electrolyte. Then the potentiostatic electrolysis was carried out at the same CO₂ bubble rate of 0.01 L min⁻¹.

LSV measurement was performed within a single chamber electrolytic cell with a three-electrode system, which included a working electrode (CuSb/NMC catalyst coated on a glassy carbon electrode, the coating amount of catalyst was also 0.6 mg cm⁻²), a Pt mesh electrode and an SCE reference electrode. A 0.1 M KHCO₃ solution was used as the electrolyte, and N₂ or CO₂

was introduced for at least 30 minutes to form a N₂- or CO₂-saturated solution (pH 8.57 and 6.80, respectively). The scanning rate is 50 mV s⁻¹. To avoid the effect of solution pH, all potentials were converted to potentials relative to the reversible hydrogen electrode by formula (1). The vertical coordinate current density of the LSV curve is determined by dividing the current value by the geometric area. The reduction current is set to be positive.

$$E(\text{vs. RHE}) = E(\text{vs. SCE}) + 0.0591 \text{ V} \times \text{pH} + 0.241 \text{ V} \quad (1)$$

The experimental device, electrode processing and preparation of electric double layer capacitance test were consistent with the LSV measurement experimental device. 0.1 M KHCO₃ solution saturated with N₂ was used as the electrolyte, and 20 mV s⁻¹, 40 mV s⁻¹, 60 mV s⁻¹, 80 mV s⁻¹, and 100 mV s⁻¹ were selected in the potential range of the non-Faraday current (0.75–0.35 V vs. RHE) for cyclic voltammetry, the formula is as follows, where I is the current density, calculated by dividing the current value by the geometric area.

$$C_{\text{dl}} = \frac{I}{\nu} \quad (2)$$

Product analysis

The gas product was detected by a gas chromatograph (GC; Agilent 7890) equipped with a flame ionization detector to detect hydrocarbons and a thermal conductivity detector to detect H₂ and CO. The liquid product was qualitatively detected by GC-2014C with HS-9A headspace injection. The Faraday efficiency of gas phase products was calculated by the following formula:

$$\text{FE} = \frac{\phi \nu t Z F}{Q V_{\text{m}}} \times 100\% \quad (3)$$

where ϕ is the volume fraction of gaseous products. ν is the flow rate of CO₂ gas ($\nu = 0.01 \text{ L min}^{-1}$). t is the electrolysis time (min). Z is the number of electrons transferred to the product (when the product is H₂ and CO, $Z = 2$; when the product is CH₄, $Z = 8$; when the product is C₂H₄, $Z = 12$). F is Faraday's constant, which is 96 500 C mol⁻¹. Q is the total quantity (C) of electric charge, used by the cell during the overall electrolysis process. V_{m} is the molar volume of gas at 298.15 K, 101 kPa, and its value is 24.04 L mol⁻¹.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

This project was supported by National Key R&D Program of China (2020YFA0710200) and National Natural Science Foundation of China (22072046).



Notes and references

- 1 W. Ma, S. Xie, T. Liu, Q. Fan, J. Ye, F. Sun, Z. Jiang, Q. Zhang, J. Cheng and Y. Wang, *Nat. Catal.*, 2020, **3**, 478–487.
- 2 A. X. Guan, Z. Chen, Y. L. Quan, C. Peng, Z. Q. Wang, S. K. Sham, C. Yang, Y. L. Ji, L. P. Qian, X. Xu and G. F. Zheng, *ACS Energy Lett.*, 2020, **5**, 1044–1053.
- 3 A. Liu, M. Gao, X. Ren, F. Meng, Y. Yang, L. Gao, Q. Yang and T. Ma, *J. Mater. Chem. A*, 2020, **8**, 3541–3562.
- 4 X. Ba, L.-L. Yan, S. Huang, J. Yu, X.-J. Xia and Y. Yu, *J. Phys. Chem. C*, 2014, **118**, 24467–24478.
- 5 J. Yuan, L. Liu, R. R. Guo, S. Zeng, H. Wang and J. X. Lu, *Catalysts*, 2017, **7**, 220–231.
- 6 C. G. Morales-Guio, E. R. Cave, S. A. Nitopi, J. T. Feaster, L. Wang, K. P. Kuhl, A. Jackson, N. C. Johnson, D. N. Abram, T. Hatsukade, C. Hahn and T. F. Jaramillo, *Nat. Catal.*, 2018, **1**, 764–771.
- 7 R. Kortlever, I. Peters, S. Koper and M. T. M. Koper, *ACS Catal.*, 2015, **5**, 3916–3923.
- 8 S. Nitopi, E. Bertheussen, S. B. Scott, X. Liu, A. K. Engstfeld, S. Horch, B. Seger, I. E. L. Stephens, K. Chan, C. Hahn, J. K. Norskov, T. F. Jaramillo and I. Chorkendorff, *Chem. Rev.*, 2019, **119**, 7610–7672.
- 9 C. W. Lee, K. D. Yang, D. H. Nam, J. H. Jang, N. H. Cho, S. W. Im and K. T. Nam, *Adv. Mater.*, 2018, **30**, e1704717.
- 10 Y. Feng, Z. Li, H. Liu, C. Dong, J. Wang, S. A. Kulinich and X. Du, *Langmuir*, 2018, **34**, 13544–13549.
- 11 X. Su, Y. Sun, L. Jin, L. Zhang, Y. Yang, P. Kerns, B. Liu, S. Li and J. He, *Appl. Catal., B*, 2020, **269**, 118800–118808.
- 12 Z. U. Ahmad, L. Yao, J. Wang, D. D. Gang, F. Islam, Q. Lian and M. E. Zappi, *Chem. Eng. J.*, 2019, **359**, 814–826.
- 13 V. S. gharahshiran and M. Yousefpour, *Int. J. Hydrogen Energy*, 2018, **43**, 7020–7037.
- 14 N. Sahin, W. O. Silva, M. R. Camilo, E. A. Ticianelli, F. H. B. Lima, J. Parmentier, C. Comminges, T. W. Napporn and K. B. Kokoh, *Sustainable Energy Fuels*, 2020, **4**, 6045–6053.
- 15 X. Wang, M. Qiu, R. L. Smith, J. Yang, F. Shen and X. Qi, *ACS Sustainable Chem. Eng.*, 2020, **8**, 18157–18166.
- 16 Z. Qin, X. Jiang, Y. Cao, S. Dong, F. Wang, L. Feng, Y. Chen and Y. Guo, *Sci. Total Environ.*, 2020, **759**, 143575–143582.
- 17 Y. Guo, J. He, T. Wang, H. Xue, Y. Hu, G. Li, J. Tang and X. Sun, *J. Power Sources*, 2011, **196**, 9299–9307.
- 18 S.-H. Liu, M.-T. Wu, Y.-H. Lai, C.-C. Chiang, N. Yu and S.-B. Liu, *J. Mater. Chem.*, 2011, **21**, 12489–12496.
- 19 Z. Lei, L. An, L. Dang, M. Zhao, J. Shi, S. Bai and Y. Cao, *Microporous Mesoporous Mater.*, 2009, **119**, 30–38.
- 20 X. Peng, Y. Mi, H. Bao, Y. Liu, D. Qi, Y. Qiu, L. Zhuo, S. Zhao, J. Sun, X. Tang, J. Luo and X. Liu, *Nano Energy*, 2020, **78**, 105321–105326.
- 21 S. Gao, Y. Liu, Z. Xie, Y. Qiu, L. Zhuo, Y. Qin, J. Ren, S. Zhang, G. Hu, J. Luo and X. Liu, *Small Methods*, 2021, **5**, 2001039–2001044.
- 22 G. H. Wang, Z. Cao, D. Gu, N. Pfander, A. C. Swertz, B. Spliethoff, H. J. Bongard, C. Weidenthaler, W. Schmidt, R. Rinaldi and F. Schuth, *Angew. Chem., Int. Ed.*, 2016, **55**, 8850–8855.
- 23 H. Li, T.-W. Jiang, X. Qin, J. Chen, X.-Y. Ma, K. Jiang, X.-G. Zhang and W.-B. Cai, *ACS Catal.*, 2021, **11**, 6846–6856.
- 24 X. Wan, Y. Li, H. Xiao, Y. Pan and J. Liu, *RSC Adv.*, 2020, **10**, 2932–2941.
- 25 D.-M. Wang, A.-C. Miller and M.-R. Notis, *Surf. Interface Anal.*, 1996, **24**, 127–132.
- 26 J.-J. Zhang, S.-L. Shan, Y. Shi, Y. Hou, H. Wang and J.-X. Lu, *J. Electroanal. Chem.*, 2021, **882**, 114962–114970.
- 27 J. Yuan, M.-P. Yang, W.-Y. Zhi, H. Wang, H. Wang and J.-X. Lu, *J. CO₂ Util.*, 2019, **33**, 452–460.
- 28 S. Gao, Y. Lin, X. Jiao, Y. Sun, Q. Luo, W. Zhang, D. Li, J. Yang and Y. Xie, *Nature*, 2016, **529**, 68–71.
- 29 S. Liu, X. F. Lu, J. Xiao, X. Wang and X. W. D. Lou, *Angew. Chem., Int. Ed.*, 2019, **58**, 13828–13833.
- 30 S. Liu, J. Xiao, X. F. Lu, J. Wang, X. Wang and X. W. D. Lou, *Angew. Chem., Int. Ed.*, 2019, **58**, 8499–8503.

