

## Metal sulfide-based nanomaterials for electrochemical CO<sub>2</sub> reduction

Mukherjee, Anirban; Abdinejad, Maryam; Mahapatra, Susanta Sinha; Ruidas, Bidhan Chandra

**DOI**

[10.1039/d2ta08209h](https://doi.org/10.1039/d2ta08209h)

**Publication date**

2023

**Document Version**

Final published version

**Published in**

Journal of Materials Chemistry A

**Citation (APA)**

Mukherjee, A., Abdinejad, M., Mahapatra, S. S., & Ruidas, B. C. (2023). Metal sulfide-based nanomaterials for electrochemical CO<sub>2</sub> reduction. *Journal of Materials Chemistry A*, 11(17), 9300-9332. <https://doi.org/10.1039/d2ta08209h>

**Important note**

To cite this publication, please use the final published version (if applicable). Please check the document version above.

**Copyright**

Other than for strictly personal use, it is not permitted to download, forward or distribute the text or part of it, without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license such as Creative Commons.

**Takedown policy**

Please contact us and provide details if you believe this document breaches copyrights. We will remove access to the work immediately and investigate your claim.

***Green Open Access added to TU Delft Institutional Repository***

***'You share, we take care!' - Taverne project***

**<https://www.openaccess.nl/en/you-share-we-take-care>**

Otherwise as indicated in the copyright section: the publisher is the copyright holder of this work and the author uses the Dutch legislation to make this work public.



Cite this: DOI: 10.1039/d2ta08209h

# Metal sulfide-based nanomaterials for electrochemical CO<sub>2</sub> reduction

Anirban Mukherjee,<sup>1</sup> Maryam Abdinejad,<sup>2</sup> Susanta Sinha Mahapatra<sup>3</sup> and Bidhan Chandra Ruidas<sup>1\*</sup>

The electrochemical CO<sub>2</sub> reduction (ECO<sub>2</sub>R) is critical to enabling the widespread use of abundant renewable energy sources. However, in order to successfully implement such technologies on an industrial scale, necessary advancement in both the material and molecular design of electrocatalysts is required. In recent years, metal-sulfide (MS)-based nanomaterials have been explored as promising electrocatalysts for ECO<sub>2</sub>R. This article provides a systematic review of the design and development of MS-based catalysts for ECO<sub>2</sub>R, including their synthesis, characterization, reaction mechanism, catalytic performance, and strategies for future optimization. The current state-of-the-art MS-based ECO<sub>2</sub>R catalysts and their technical challenges are outlined herein with the purpose of establishing new guidelines for the rational design of next generation MS-based catalysts for CO<sub>2</sub> electroreduction.

Received 20th October 2022  
Accepted 6th April 2023

DOI: 10.1039/d2ta08209h

rsc.li/materials-a

## 1 Introduction

The excessive usage of fossil fuels leads to their rapid depletion, CO<sub>2</sub> emission, and other toxic gases in the atmosphere, resulting in global warming and climate change.<sup>1,2</sup> To overcome this problem, a decrease in CO<sub>2</sub> emissions through effective CO<sub>2</sub> capture, utilization, and storage approach has been considered in the past few years (Fig. 1).<sup>3,4</sup> The conversion of carbon dioxide to valuable products has emerged as a promising technology for CO<sub>2</sub> utilization over the past decades, which can be executed *via* thermochemical,<sup>5</sup> photochemical,<sup>6</sup> photoelectrochemical,<sup>7</sup> electrochemical,<sup>8</sup> and biochemical<sup>9</sup> processes. Among all, the electrochemical CO<sub>2</sub> reduction (ECO<sub>2</sub>R) to valuable chemicals and chemical feedstocks such as small C<sub>1</sub> products (mainly carbon monoxide, formic acid methane, and methanol)<sup>10–13</sup> and high-energy dense C<sub>2+</sub> products (ethylene, ethanol, *n*-propanol),<sup>14–16</sup> has drawn significant attention among the aforementioned processes due to its (a) tunability of the procedure (*e.g.*, potential and temperature), (b) compatibility with media (*e.g.*, organic and aqueous), and (c) scalability.<sup>17,18</sup>

However, the ECO<sub>2</sub>R is challenging due to the stable and chemically inert linear CO<sub>2</sub> molecule.<sup>19,20</sup> CO<sub>2</sub> transformation is driven by nucleophilic attacks at the carbon molecule, which is an energy uphill procedure requiring a considerable input of energy (750 kJ mol<sup>-1</sup> required to break the C=O bond) and

convert to valuable chemicals.<sup>21</sup> The conversion mechanism is a complex process that involves multiple proton-coupled electron transfers (PCET) and may comprise several side reactions and intermediates.<sup>22</sup> In this regard, the electrocatalysts are instrumental in ECO<sub>2</sub>R to overcome the kinetically sluggish reaction and promote the PCET reaction. Therefore, early research emphasized developing different solid-state electrocatalysts and discovering several reaction intermediates or final products formed during catalysis.

When conducted in aqueous electrolytes, the ECO<sub>2</sub>R inhibits by competition from the HER (Hydrogen Evolution Reaction), which occurs in the same potential window as the ECO<sub>2</sub>R but with lower thermodynamic barriers due to the energetically favorable proton adsorption and reduction than CO<sub>2</sub> activation. Evidently, the high stability of the CO<sub>2</sub> molecule necessitates the use of large overpotentials for the reactant to be adsorbed and activated at the active site. However, the HER outperforms the ECO<sub>2</sub>R due to faster kinetics at high overpotentials, resulting in a high FE (Faradaic Efficiency) for hydrogen generation at

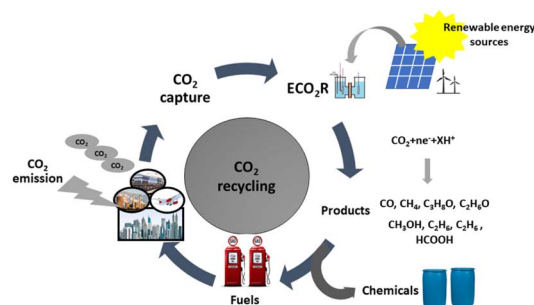


Fig. 1 A schematic representation of closed-loop CO<sub>2</sub> recycling.

<sup>1</sup>Department of Chemical Engineering, Birla Institute of Technology, Mesra, Ranchi 835215, India. E-mail: bidhanruidas@gmail.com

<sup>2</sup>Materials for Energy Conversion and Storage (MECS), Department of Chemical Engineering, The Delft University of Technology, van der Maasweg 9, 2629 HZ Delft, The Netherlands

<sup>3</sup>Department of Chemistry, Birla Institute of Technology, Mesra, Ranchi 835215, India

the expense of selectivity for CO<sub>2</sub> reduction products. Therefore, special attention should be paid to the design of catalyst systems that maximize product selectivity for ECO<sub>2</sub>R and suppress proton reduction as much as possible. So far, according to the final product selectivity, ECO<sub>2</sub>R catalysts are divided into four classes.<sup>22</sup> For instance: – (i) Cd, Hg, Sn, In, Bi, Pb: produce formate as the primary product with high faradaic efficiencies;<sup>23–27</sup> (ii) Au, Ag, Zn, Pd: provide high binding strength of \*COOH intermediates into electrode surface resulting in a fast reduction to \*CO intermediates followed by CO production;<sup>28–35</sup> (iii) Ni, Fe, Si, V, Pt: produce H<sub>2</sub> due to the low overpotential towards hydrogen evolution reaction (HER);<sup>36–39</sup> (iv) Cu yield 16 valuable compounds under different operating conditions, including various multi-carbon products depending on the \*COH or \*CHO intermediates.<sup>40</sup> In this regard, Hori *et al.*<sup>41</sup> performed ECO<sub>2</sub>R in 0.5 M KHCO<sub>3</sub> at 5 mA cm<sup>-2</sup> for one hour on different polycrystalline metal electrodes. The results are illustrated in Table 1.<sup>42</sup> This Table 1 exhibits that a significant overpotential is required for each metal electrode to achieve a specific current density (here –5 mA cm<sup>-2</sup>). The lowest overpotential (0.6 V) is required for Au to obtain CO (87%), while the highest (1.1 V) is required for Pb to obtain formate (97%). In addition to the aforementioned transition metal electrocatalysts, metal oxides (MOs),<sup>43,44</sup> MXenes,<sup>45,46</sup> transition metal chalcogenides (TMDs),<sup>47,48</sup> metal-functionalized porphyrin-based structures,<sup>49,50</sup> nitrogen-based electrocatalysts,<sup>51–53</sup> and aerogels<sup>54,55</sup> are also reported to have promising catalytic ECO<sub>2</sub>R activity.

Despite the significant advancement that has been achieved, some bottlenecks still exist with the practical application of ECO<sub>2</sub>R, including high overpotential, slow reaction rate resulting in low current densities, competitive HER, poor product selectivity, and unsatisfactory stability.<sup>56,57</sup> First, the process requires high overpotential and predominantly suffers from considerable energy input due to the thermodynamic stability

of CO<sub>2</sub> molecules. Then, the complex PCET steps and the low solubility of the CO<sub>2</sub> in an aqueous electrolyte hinder the electron transfer kinetics. The low current density ( $j < 200 \text{ mA cm}^{-2}$ ) and poor faradaic efficiency (FE < 90%) are insufficient to meet the scale-up demands.<sup>58–60</sup> As the reduction process produces several products and intermediates, it makes the reaction paths more complex. Finally, the reaction selectivity is found to be considerably lower due to a competitive HER.<sup>61</sup> For these scenarios, advanced research efforts have been desired to design and develop novel, economic, and robust electrocatalysts that can convert CO<sub>2</sub> at high rates with a minimum overpotential.

Considering those limitations, metal-sulfide-based (MS-based) nanomaterials are particularly attractive as possible electrocatalysts or precursors due to their unique properties, such as high electrical conductivity and good electrochemical stability compared to their corresponding metal oxide field.<sup>62–67</sup> Furthermore, the following properties make them a flexible class of materials for the design of electrocatalysts: (1) higher electrical conductivity than other semiconductor materials, layered MS-based nanomaterials often have good metallic conductivity.<sup>68,69</sup> (2) Adjustable composition, crystalline phase, structural and morphological features of functional materials.<sup>70,71</sup> (3) An appropriate band gaps. The band gap has a direct impact on d-orbital filling and electronic character. At the Fermi energy level ( $E_f$ ), the density of states is dominated by d-orbital electron states.<sup>72,73</sup> (4) Different atomic vibration modes, which will directly affect the surface state of the catalyst and the adsorption mode of the reaction intermediates, so it is directly related to the active sites.<sup>74</sup> These remarkable properties motivated extensive research on every aspect of these materials, with innumerable works investigating their electronic structure, synthesis techniques, and catalytic performance for ECO<sub>2</sub>R. Indeed, the design of ECO<sub>2</sub>R catalytic systems capable of overcoming all bottlenecks is becoming a critical topic in the

Table 1 Different metals with the FE of several products produced at a particular potential and constant current density<sup>a</sup>

Group no.	Metal	$E$ (V vs. RHE)	$j_{\text{total}}$ (mA cm <sup>-2</sup> )	CO (%)	CH <sub>4</sub> (%)	C <sub>2</sub> H <sub>4</sub> (%)	EtOH (%)	PrOH (%)	HCOO <sup>-</sup> (%)	H <sub>2</sub> (%)	Total (%)
(i)	Pb	-1.24	5.0	0	0	0	0	0	97.4	5.0	102.4
	Hg	-1.12	5.0	0	0	0	0	0	99.5	0	99.5
	Tl	-1.21	5.0	0	0	0	0	0	95.1	6.2	101.3
	In	-1.16	5.0	2.1	0	0	0	0	94.9	3.3	100.3
	Sn	-1.09	5.0	7.1	0	0	0	0	88.4	4.6	100.1
(ii)	Cd	-1.24	5.0	13.9	1.3	0	0	0	78.4	9.4	103.0
	Au	-0.65	5.0	87.1	0	0	0	0	0.7	10.2	98.0
	Ag	-0.98	5.0	81.5	0	0	0	0	0.6	12.4	94.6
	Zn	-1.15	5.0	79.4	0	0	0	0	6.1	9.9	95.4
	Pd	-0.81	5.0	28.3	2.9	0	0	0	2.8	26.2	60.2
(iii)	Ga	-0.85	5.0	23.2	0	0	0	0	0	79.0	102.0
	Ni	-1.09	5.0	0	1.8	0.1	0	0	1.4	88.9	92.4
	Fe	-0.52	5.0	0	0	0	0	0	0	94.8	94.8
	Pt	-0.68	5.0	0	0	0	0	0	0.1	95.7	95.8
	Ti	-1.21	5.0	Tr	0	0	0	0	0	99.7	99.7
(iv)	Cu	-1.05	5.0	1.3	33.3	25.5	5.7	3.0	9.4	20.5	103.5

<sup>a</sup> The potential values have been converted from the reported standard hydrogen electrode (SHE) potential to the reversible hydrogen electrode (RHE) scale [ $T = 18.5 \text{ }^\circ\text{C}$ ,  $\text{pH} = 6.8$ ] by adding  $(RT/F) \ln 10 \text{ pH} = 0.39 \text{ V}$ : (Copyright 2019, American Chemical Society)<sup>12</sup>

context of the widespread adoption of these electrocatalytic technologies. Till now, several physical and chemical methodologies have been developed for preparing high-quality MS-based nanomaterials, including mono, bi, and multi-metallic sulfides.<sup>75</sup> Based on those methodologies, synthesis methods are divided into a 'top-down' and 'bottom-up approach'.<sup>76–78</sup> The top-down approach uses mechanical methods to crush bulk materials into smaller pieces to generate nanoparticles. Many top-down approaches, including sputtering,<sup>79,80</sup> electrospinning,<sup>81,82</sup> lithography,<sup>83,84</sup> ball-milling,<sup>85,86</sup> exfoliation,<sup>87–90</sup> *etc.*, are already reported in the literature for MS-based nanomaterials synthesis. The bottom-up technique is a well-known approach to synthesizing structures of nanomaterials made atom-by-atom or molecule-by-molecule. The atoms/molecules are attached through covalent or non-covalent bonds.<sup>91</sup> The commonly used bottom-up approaches are chemical vapour decomposition,<sup>92,93</sup> atomic layer deposition,<sup>94,95</sup> spray pyrolysis,<sup>96,97</sup> pulsed layer deposition,<sup>98,99</sup> thermal deposition,<sup>100,101</sup> combustion,<sup>102,103</sup> micro-emulsion,<sup>104,105</sup> precipitation,<sup>106,107</sup> hydrothermal,<sup>108–111</sup> solvothermal,<sup>112,113</sup> sulfidation,<sup>114,115</sup> microwave irradiation,<sup>116–118</sup> and electrodeposition.<sup>119,120</sup> Thus, the strong connections between the various nanomaterials and their unique properties have encouraged research to perform the controlled fabrication of noble electrocatalysts with modified nanostructures.

This review attempts to fill the gap and create a pedagogical guide on the morphology and structural variation of MS-based nanomaterials in terms of their unique capacity and control over the CO<sub>2</sub> reduction process. It provides an overview of the various synthesis methods for MS-based nanomaterials preparation and their structural, chemical, and physical properties modification for ECO<sub>2</sub>R. The correlation between synthesis methods, metal loading, sulfur concentration, morphology, and structures to the catalytic activity will also be summarized. Finally, insights on future research and development of MS-based compounds for next-generation ECO<sub>2</sub>R catalysts will be discussed.

## 2 Metal-sulfide-based electrocatalysts for ECO<sub>2</sub>R

MS-based electrocatalysts composed of metal and sulfur are now the alternatives for researchers due to their tunable and unique chemical structures, which can be synthesized through a green process.<sup>121</sup> This review categorizes MS-based catalysts into ten effective systems, including copper, cadmium, bismuth, indium, molybdenum, lead, tin, titanium, and zinc (Table 2). Subsequently, their electroreduction properties are also explored.

### 2.1 Copper-based sulfide

The copper sulfide system shows various stoichiometric structures over a wide range. Their structures varies from copper-rich to copper-deficient (Cu<sub>2</sub>S to CuS<sub>2</sub>), such as chalcocite Cu<sub>2</sub>S, djurleite Cu<sub>1.96</sub>S, digenite Cu<sub>1.8</sub>S, anilite Cu<sub>1.75</sub>S, geerite (Cu<sub>1.6</sub>S), spionkopite (Cu<sub>1.39</sub>S), yarrowite (Cu<sub>1.12</sub>S), covellite CuS

and villamaninite (CuS<sub>2</sub>).<sup>122–126</sup> Owing to their variations in phase states, morphologies, and crystal structures, these copper sulfide systems have been used in many applications, including photocatalysis,<sup>127</sup> optoelectronic devices,<sup>128</sup> sensors,<sup>129</sup> batteries,<sup>130</sup> supercapacitors,<sup>131</sup> and many others. This section is designed to summarize several strategies of copper sulfide-based electrocatalysts in converting CO<sub>2</sub> into valuable products.

**2.1.1 Substrate coupling.** The deposition of a thin, nanometer layer of metal sulfide catalyst on top of a substrate material with well-defined morphological and electrical properties makes possible the optimization of the exposure of the active sites and the maximization of the electrochemical surface area (ECSA) of the resulting catalytic framework. This technique was widely used for electrocatalysis and was thoroughly discussed in comprehensive review works.<sup>132,133</sup> Coupling the catalyst layer with a conductive substrate with controlled morphology is specifically effective for metal sulfides. Indeed, despite their high intrinsic activity, these materials are usually synthesized by low-temperature routes to obtain mesoporous structures with suboptimal exposure of active sites. On the other hand, the coupling with conductive supports, drastically improves the ECSA as well as the conductivity of the architecture.<sup>134–136</sup> In this regard, Kahsay *et al.*<sup>137</sup> presented a unique and straightforward successive ionic layer adsorption reaction (SILAR) method to deposit CuS onto a thermally produced Cu<sub>2</sub>O/CuO heterostructure. At low overpotential, the modified electrocatalyst showed good selectivity for formate production. Cu<sub>2</sub>O/CuO/CuS electrode achieved a FE<sub>Formate</sub> of 84% with a partial current density ( $j_{\text{HCOO}^-}$ ) of  $-20 \text{ mA cm}^{-2}$  at an overpotential of  $-0.7 \text{ V vs. RHE}$ , which is higher as compared to metallic Cu nanowires (FE<sub>CO</sub> = 60%). Similarly, Li *et al.*<sup>138</sup> reported that highly porous Cu<sub>2</sub>O/CuS nanocomposites (Fig. 2), which exhibit a FE<sub>Formate</sub> of 67.6% with a  $j_{\text{HCOOH}}$  value of  $15.3 \text{ mA cm}^{-2}$  at  $-0.5 \text{ V vs. RHE}$ . More importantly, it maintained an average faradaic efficiency of 62.9% at the same applied potential for at least 30 hours. The synergistic effect between the Cu nanoparticles and S concentration reduced the activation energy barrier for conversion of the COOH\* intermediates and enabled the CO<sub>2</sub> conversion at low potentials. That way, the rate of HCOOH generation was boosted. In above-mention both the cases the current density was much higher than that of the unsupported CuS electrocatalyst.

On the other hand, the coupling with conductive supports, usually carbon-based, drastically improves the electrochemical surface area as well as the conductivity of the framework. In this context, Oversteeg *et al.*<sup>139</sup> investigated the role of carbon-supported copper sulfide (CuS@C and Cu<sub>2</sub>S@C) catalysts prepared *via* a liquid phase sulfidation of CuO@C nanoparticles (Fig. 3a–f). They did cyclic voltammetry and *in situ* X-ray absorption spectroscopy experiments, which revealed that CuS@C and Cu<sub>2</sub>S@C nanoparticles undergo metallic Cu reduction during CO<sub>2</sub> electroreduction. Later, the group reported that compared to the CuO@C-derived catalyst, the selectivity towards the formate synthesis was increased at low current densities for the CuS@C- and Cu<sub>2</sub>S@C- derived catalysts. Surprisingly, with less than 4% carbon surface coverage, the catalyst obtained a maximum of 12% FE for overall formate

Table 2 A state of the art summary of MS-based catalysts for CO<sub>2</sub>R

Electrode	Synthesis method	Potential	Electrolyte	Main products	Reactor	Current density (mA cm <sup>-2</sup> )	FE (%)	Stability	Ref.
Cu <sub>2</sub> O/CuO/CuS	Successive ionic layer adsorption and reaction method (SILAR)	-0.7 V <sub>RHE</sub>	0.1 M KHCO <sub>3</sub>	HCOOH	H-cell	$j_{\text{HCOO}^-} = 20$	84	2.5 h	137
Cu <sub>2</sub> S/Cu <sub>2</sub> O	Hydrothermal method followed by electrochemical treatment	-0.9 V <sub>RHE</sub>	0.1 M KHCO <sub>3</sub>	HCOOH	H-cell	$j_{\text{HCOO}^-} = 12.3$	67.6	30 h	138
Cu <sub>2</sub> S@C	Wetness impregnation method followed by drying and heat treatment	-0.78 ± 0.02 V <sub>RHE</sub>	0.5 M KCl + 0.5 M KHCO <sub>3</sub>	HCOOH	H-cell	$j_{\text{total}} = 1.5$	12	5 h	139
Cu <sub>1.81</sub> S@MWCNT-600-OD	<i>In situ</i> crystallization strategy	-0.67 V <sub>RHE</sub>	0.5 M KHCO <sub>3</sub>	HCOOH	H-cell	$j_{\text{total}} = 3.75$	82	20 h	140
Submicron-sized Cu-S	Solvothetical method	-0.8 V <sub>RHE</sub>	0.1 M KHCO <sub>3</sub>	HCOOH	H-cell	$j_{\text{total}} = \sim 10$	80	12 h	145
Cu <sub>4</sub> S	Dipping	-0.6 V <sub>RHE</sub>	0.1 M KHCO <sub>3</sub>	HCOOH	H-cell	$j_{\text{HCOOH}} = 2.5$	72	72 h	146
Cu <sub>2</sub> S/Cu-foam	Electrodeposition method	-2.0 V (vs. Ag/Ag <sup>+</sup> )	0.5 mol L <sup>-1</sup> BmimBF <sub>4</sub>	HCOOH	H-cell	$j_{\text{HCOOH}} = 5.3$	85	6 h	149
Hollow CuS microcubes	Galvanic replacement method	-0.16 V <sub>RHE</sub>	0.5 M KHCO <sub>3</sub>	CO	H-cell	—	32.7	10 h	150
CuS-thiourea precursors	Hydrothermal method	-0.51 V <sub>RHE</sub>	0.1 M KHCO <sub>3</sub>	CO	H-cell	—	72.67	5 h	151
CuS nanosheet arrays on Ni foam	Hydrothermal method	-1.1 V <sub>RHE</sub>	0.1 M KHCO <sub>3</sub>	CH <sub>4</sub>	H-cell	$j_{\text{total}} = 7.32$	73.5 ± 5	60 h	152
CuS nanoflowers	Ethylene glycol solvothermal method	-0.8 V <sub>RHE</sub> to -1.0 V <sub>RHE</sub>	0.1 M KHCO <sub>3</sub>	HCOOH	H-cell	$j_{\text{formate}} = \sim 6.5$	~52	2 h	153
CuS/BM coated with PTFE	Chemical bath deposition method	-0.7 V <sub>RHE</sub>	0.5 mol L <sup>-1</sup> KHCO <sub>3</sub>	HCOOH	H-cell	$j_{\text{formate}} = 50$	70	1.5 h	154
MOF-derived hierarchical CuS hollow polyhedron	MOF self-sacrificial template method	-0.6 V <sub>RHE</sub>	0.5 M K <sub>2</sub> SO <sub>4</sub> aqueous solution	HCOOH	H-cell	$j_{\text{formate}} = \sim 16$	>90	36 h	155
Polycrystalline Cu nanoparticles (Cu-s)	Electrochemical reduction	-1.2 V <sub>RHE</sub>	0.1 M KHCO <sub>3</sub>	C <sub>2</sub> H <sub>4</sub>	H-cell	$j_{\text{C}_2\text{H}_4} = 40.8$	68.6	8 h	156
AC-CuS <sub>x</sub>	Electrodeposition method	-0.9 V <sub>RHE</sub>	0.1 M KHCO <sub>3</sub>	HCOOH	H-cell	$j_{\text{HCOO}^-} = 9$	75	3 h	158
Sulfur-doped Cu <sub>2</sub> O-derived Cu catalyst (Cu-5000S)	Electrodeposition followed by immersion	-0.8 V <sub>RHE</sub>	0.1 M KHCO <sub>3</sub>	HCOOH	H-cell	$j_{\text{HCOO}^-} = 13.9$	~75	12 h	159
Cu <sub>2</sub> S nanocrystals	Electrochemically driven cation exchange method	-0.9 V <sub>RHE</sub>	0.1 M NaHCO <sub>3</sub>	HCOOH	H-cell	$j_{\text{HCOO}^-} = 19$	87.3	9 h	160
Bimetallic sulfide nanosheets (Cu-nano-x)	Electrochemically driven cation exchange method	-0.2 V <sub>RHE</sub>	0.05 M K <sub>2</sub> CO <sub>3</sub>	HCOOH	H-cell	—	~70	16 h	161
Cu <sub>2</sub> S-Cu-V (V denoted as vacancy)	Solvothermal method followed by electrochemical reduction	-0.95 V <sub>RHE</sub>	1.0 M KOH	Multi-carbon alcohols	Flow cell	$j_{\text{multi-carbon alcohols}} = 120$	32	16 h	165
Double sulfur vacancy-rich CuS	Electrochemical lithium tuning strategy	-1.05 V <sub>RHE</sub>	0.1 M KHCO <sub>3</sub>	<i>n</i> -propanol	H-cell	$j_{\text{n-propanol}} = 9.9$	15.4 ± 1	10 h	166
SnO <sub>2</sub> confined on CuS nanosheets	One-pot precipitation synthesis	-1.0 V <sub>RHE</sub>	0.1 M KHCO <sub>3</sub>	CO	H-cell	$j_{\text{CO}} = 15.24$	>85	24 h	168
Heterostructure Bi-Cu <sub>2</sub> S nanocrystals	One-pot solution-phase method	-1.0 V <sub>RHE</sub>	0.1 M KHCO <sub>3</sub>	HCOOH	H-cell	$j_{\text{HCOO}^-} = \sim 17$	>98	10 h	169

Table 2 (Contd.)

Electrode	Synthesis method	Potential	Electrolyte	Main products	Reactor	Current density (mA cm <sup>-2</sup> )	FE (%)	Stability	Ref.
CuInS <sub>2</sub> hollow nanostructures	Template-free method	-0.7 V <sub>RHE</sub> & -1.0 V <sub>RHE</sub>	0.1 M KHCO <sub>3</sub>	HCOOH & CO	H-cell	$j_{\text{total}} \sim 13$	72.8 & 82.3	4 h	170
Cu-S motif is dispersed in the framework of HKUST-1 (S-HKUST-1)	Hydrothermal method	-1.94 V <sub>RHE</sub>	1.0 M KOH	C <sub>2</sub> H <sub>4</sub>	Flow cell	$J_{\text{C}_2\text{H}_4} = 228$	57.2	8 h	171
Porous Cd modified by sulfur	Liquid-phase synthesis strategy	-0.8 V <sub>RHE</sub>	0.5 M KHCO <sub>3</sub>	CO	H-cell	$j_{\text{co}} = 89.8$	88	10 h	183
Cadmium sulfide (CdS) nanoneedle arrays	Microwave heating strategy	-1.2 V <sub>RHE</sub>	0.1 M KHCO <sub>3</sub>	CO	Flow-cell	$j_{\text{co}} = 212$	95.5 ± 4.0	24 h	184
CdS <sub>x</sub> Se <sub>1-x</sub> nanorods	Solvothermal method	-1.2 V <sub>RHE</sub>	0.1 M KHCO <sub>3</sub>	CO	H-cell	$j_{\text{co}} \sim 22$	81	10 h	185
CdS nanorods	Solvothermal method	-0.8 to -1.1 V <sub>RHE</sub>	0.5 M KHCO <sub>3</sub>	CO	H-cell	$j_{-0.9 \text{ V}(\text{CO})} \sim 1.3$	95	40 h	190
CdS surface with S vacancy	Solvothermal method	-1.1 V <sub>RHE</sub>	0.5 M KHCO <sub>3</sub>	CO	H-cell	$j_{\text{co}} = 20.5$	100 ± 0.5	10 h	191
Cadmium sulfide and carbon nanotubes composite catalyst (CdS-CNTs)	Solvothermal method	-1.2 V <sub>RHE</sub>	0.1 M KHCO <sub>3</sub>	CO	H-cell	$j_{\text{total}} \sim 13$	~95	10 h	192
CdS/Ti <sub>3</sub> C <sub>2</sub> MXene	Solvothermal method	-1.0 V <sub>RHE</sub>	0.1 M KHCO <sub>3</sub>	CO	H-cell	$j_{\text{co}} \sim 6$	94	8 h	198
Ag <sub>2</sub> S nanodots modified CdS nanorods	Co-solvothermal process	-1.1 V <sub>RHE</sub>	0.5 M KHCO <sub>3</sub>	CO	Flow-cell	$j_{\text{co}} = 10.6$	95	20 h	199
SD-CuCd <sub>2</sub>	Co-precipitation method	-0.8 V <sub>RHE</sub>	0.1 M KHCO <sub>3</sub>	Ethanol	H-cell	$j_{\text{co}} = 0.6$	32	6 h	201
Ag-SnS <sub>2</sub>	Polyol method	-0.1 V <sub>RHE</sub>	0.5 M KHCO <sub>3</sub>	HCOOH & CO/H <sub>2</sub>	H-cell	$j_{\text{formate}} = 23.3$ , $j_{\text{CO}/\text{H}_2} = 15.5$	60, 20.5	10 h	227
Atomically thin SnS <sub>2</sub> nanosheets with 5% Ni doping	Solvothermal method	-0.9 V <sub>RHE</sub>	0.1 M KHCO <sub>3</sub>	CO & HCOOH	H-cell	$j_{\text{total}} = 19.6$	93	8 h	228
Sulfur modulated tin catalysts (Sn(S)/Au)	Atomic layer deposition of SnS <sub>x</sub> followed by a reduction process	-0.75 V <sub>RHE</sub>	0.1 M KHCO <sub>3</sub>	HCOOH	H-cell	$j_{\text{HCOOH}} = 51$	93.3	40 h	229
SnS/aminated-C	Modified hard template-induced method	-0.9 V <sub>RHE</sub>	0.5 M KHCO <sub>3</sub>	HCOOH	H-cell	$j_{\text{HCOOH}} = 41.1$	92.6	15 h	230
SnS <sub>2</sub> /rGO	Hydrothermal method	-1.4 V <sub>RHE</sub>	0.5 M NaHCO <sub>3</sub>	HCOOH	H-cell	$j_{\text{HCOOH}} = 11.75$	84.5	2 h	231
SnS <sub>2</sub> monolayers	Li-intercalation/exfoliation method	-0.8 V <sub>RHE</sub>	0.1 M KHCO <sub>3</sub>	HCOOH	H-cell	$j_{\text{total}} \sim 45$	94 ± 5	80 h	232
Nitrogen-enriched Sn(S) nanosheets	Nitrogen plasma engraving and topo-chemical electroreduction	-0.7 V <sub>RHE</sub>	0.1 M KHCO <sub>3</sub>	HCOOH	Flow-cell	$j_{\text{total}} = 25$	93.3	20 h	233
Stable semimetal 1H-SnS <sub>2</sub>	Hydrogen-assisted low temperature calcination	-0.8 V <sub>RHE</sub>	0.1 M KHCO <sub>3</sub>	CO	H-cell	$j_{\text{co}} = 10.9$	98.2	15 h	234
S doped-Bi <sub>2</sub> O <sub>3</sub> -CNT	Solvothermal method	-0.9 V <sub>RHE</sub>	0.5 M KHCO <sub>3</sub>	HCOOH	H-cell	$j_{\text{HCOOH}} = 48.64$	97.06	10 h	244
Sulfur-derived Bi	Hydrothermal method	-0.75 V <sub>RHE</sub>	0.5 M NaHCO <sub>3</sub>	HCOOH	H-cell	$j_{\text{total}} = 5$	84	24 h	245
Bi <sub>2</sub> S <sub>3</sub> -Bi <sub>2</sub> O <sub>3</sub> @rGO	Partial precipitation conversion method	-0.9 V <sub>RHE</sub>	0.1 M KHCO <sub>3</sub>	HCOOH	H-cell	$j_{\text{HCOOH}} \sim 3.8$	90	24 h	246

Table 2 (Contd.)

Electrode	Synthesis method	Potential	Electrolyte	Main products	Reactor	Current density (mA cm <sup>-2</sup> )	FE (%)	Stability	Ref.
Bi-Bi <sub>2</sub> S <sub>3</sub>	Solvothermal method	-1.0 V <sub>RHE</sub>	0.1 M KHCO <sub>3</sub>	HCOOH	H-cell	<i>j</i> <sub>formate</sub> = ~14	85	12 h	247
Sulfur-modulated bismuth sub carbonate nanosheets (S-BiOC)	Solvothermal method	-0.9 V <sub>RHE</sub>	0.5 M KHCO <sub>3</sub>	HCOOH	H-cell	<i>j</i> <sub>formate</sub> = 29	>90	20 h	249
Bulk MoS <sub>2</sub> with Mo-terminated edge	Chemical vapor deposition method	-0.764 V <sub>RHE</sub>	4 mol% EMIM-BF <sub>4</sub> solution	CO	H-cell	<i>j</i> <sub>co</sub> = 65	98	10 h	256
rGO-PEI-MoS <sub>x</sub>	Drop casting followed by electrodeposition	-0.65 V <sub>RHE</sub>	0.5 M NaHCO <sub>3</sub>	CO	H-cell	<i>j</i> <sub>total</sub> = 55	85.1	—	263
N-MoS <sub>2</sub> @NCDS-180	Solvothermal method	-0.9 V <sub>RHE</sub>	6 mol% EMIM-BF <sub>4</sub> solution	CO	H-cell	<i>j</i> <sub>CO/H<sub>2</sub></sub> = 36.2	90.2	10 h	264
Cu-g-C <sub>3</sub> N <sub>4</sub> /MoS <sub>2</sub>	Hydrothermal method	-0.67 V <sub>RHE</sub>	0.5 M KHCO <sub>3</sub>	CH <sub>3</sub> OH	H-cell	<i>j</i> <sub>methanol</sub> = 78	19.7	30 h	265
Edge-exposed 2H MoS <sub>2</sub> N-doped carbon hybridization	ZIF-assisted method	-0.7 V <sub>RHE</sub>	4 mol% EMIM-BF <sub>4</sub> solution	CO	H-cell	<i>j</i> <sub>co</sub> = 34.31	92.68	24 h	266
Cu/MoS <sub>2</sub>	Microwave hydrothermal method	-1.4V <sub>SCE</sub>	0.1 M KHCO <sub>3</sub>	CH <sub>4</sub>	H-cell	<i>j</i> <sub>CH<sub>4</sub></sub> = ~3.2	17.08	48 h	267
5% Nb-doped on vertically oriented MoS <sub>2</sub>	Chemical vapor deposition method	-0.8 V <sub>RHE</sub>	50 vol% EMIM-BF <sub>4</sub>	CO	H-cell	<i>j</i> <sub>total</sub> = 237	80	—	268
Cu <sub>2</sub> O nanoparticles decorated onto the MoS <sub>2</sub> nanosheets	Solution chemistry method	-1.3 V <sub>RHE</sub> and -1.1 V <sub>RHE</sub>	0.5 M KHCO <sub>3</sub>	Methanol & ethanol	H-cell	<i>j</i> <sub>total</sub> = 113	12.3 & 7.9	2 h	269
Hydrophobic exfoliated MoS <sub>2</sub> with decoration of fluorosilane	Ball milling method	-0.9 V <sub>RHE</sub>	6 mol% EMIM-BF <sub>4</sub> solution	CO	H-cell	—	81	10 h	270
MoSeS alloy monolayers	Liquid-liquid interface-mediated strategy	-0.15 V <sub>RHE</sub>	4 mol% EMIM-BF <sub>4</sub> solution	CO	H-cell	<i>j</i> <sub>CO/H<sub>2</sub></sub> = 43	45.2	10 h	276
In nanoparticles on In <sub>2</sub> S <sub>3</sub> nanosheets	Hydrothermal method	-1.0 V <sub>RHE</sub>	1 M KHCO <sub>3</sub>	HCOOH	H-cell	<i>j</i> <sub>formate</sub> = 40.3	76	8 h	282
Mn-doped In <sub>2</sub> S <sub>3</sub> nanosheets	Modified thermal decomposition method	-0.9 V <sub>RHE</sub>	0.1 M KHCO <sub>3</sub>	HCOOH	H-cell	<i>j</i> <sub>total</sub> = 20.1	90	8 h	283
ZnIn <sub>2</sub> S <sub>4</sub>	Hydrothermal method	-1.18 V <sub>RHE</sub>	1 M KHCO <sub>3</sub>	HCOOH	Flow cell	<i>j</i> <sub>formate</sub> = ~298	99.3	60 h	284
Flowerlike In <sub>2</sub> S <sub>3</sub>	Ionothermal method	-2.3 V <sub>RHE</sub>	BmimPF <sub>6</sub> /MeCN-H <sub>2</sub> O solution	HCOOH & CO	H-cell	<i>j</i> <sub>formate</sub> = 25.6	86	10 h	285
Sulfur-doped indium	Hydrothermal followed by electroreduction	-0.98 V <sub>RHE</sub>	0.1 M KHCO <sub>3</sub>	HCOOH	H-cell	<i>j</i> <sub>total</sub> = 84	93	10 h	286
Wafer structured sulfur-derived Pb	Electroreduction	-1.08 V <sub>RHE</sub>	0.1 M KHCO <sub>3</sub>	HCOOH	H-cell	<i>j</i> <sub>HCOOH</sub> = 12	88	—	288
PbS nanocrystals	Hot injection colloidal method	-1.2 V <sub>RHE</sub>	0.1 M KHCO <sub>3</sub>	HCOOH	H-cell	—	97.6 ± 5.3	10 h	289
ZnS/Zn	Sulfur infiltration method	-2.4 V <sub>Fe/Fe'</sub>	Propylene carbonate/ <i>j</i> <sub>CO/H<sub>2</sub></sub> = 6.4	HCOOH	H-cell	—	—	—	298
(CH <sub>3</sub> CH <sub>2</sub> CH <sub>2</sub> ) <sub>4</sub> N(ClO <sub>4</sub> )	CO	H-cell	0.1 M KHCO <sub>3</sub>	92	4 h	297	—	—	298
S-Zn-S nanosheets	Chemical vapor deposition	-0.8 V <sub>RHE</sub>	0.1 M KHCO <sub>3</sub>	CO	H-cell	<i>j</i> <sub>co</sub> = ~11	94.2	15 h	298



Table 2 (Contd.)

Electrode	Synthesis method	Potential	Electrolyte	Main products	Reactor	Current density (mA cm <sup>-2</sup> )	FE (%)	Stability	Ref.
ZnS/ZnO interface	Hydrothermal followed by centrifugation and sulfuration	-0.56 V <sub>RHE</sub>	1 M KOH	CO	H-cell	$j_{CO} \approx 109$	97.2 ± 0.5	40 h	299
Semi-metallic titanium disulfide (TiS <sub>2</sub> )	Atomic layer deposition	-0.5 V <sub>RHE</sub>	0.1 M NBu <sub>4</sub> -PF <sub>6</sub>	CO	H-cell	$j_{CO} = 5$	83	16 h	302
Ni <sub>2</sub> FeS <sub>4</sub> nanosheets	Microwave-assisted non-aqueous sol-gel method	-0.7 V <sub>RHE</sub>	0.1 M KHCO <sub>3</sub>	CO	H-cell	—	5.9	1 h	303
FeS <sub>2</sub> /NiS nanocomposite	Hydrothermal method	-0.6 V <sub>RHE</sub>	0.5 M KHCO <sub>3</sub>	CH <sub>3</sub> OH	H-cell	$j_{total} = 3.1$	64	4 h	304
Bulk Fe/Ni sulfides (Fe <sub>4.5</sub> Ni <sub>4.5</sub> S <sub>8</sub> pentlandite)	High-temperature synthesis	-1.80 V <sub>NHE</sub>	0.1 M TBAPF <sub>6</sub>	CO & methane	H-cell	$j_{total} = 3$	87 & 13	15 h	305
Fe <sub>3</sub> Ni <sub>6</sub> S <sub>8</sub>	High-temperature synthesis	-1.80 V <sub>NHE</sub>	0.1 M TBAPF <sub>6</sub> /acetonitrile solution	CO	H-cell	$j_{total} = 15$	3.6	8 h	306
Fe <sub>4.5</sub> Ni <sub>4.5</sub> S <sub>4</sub> Se <sub>4</sub>	Hot pressing method	-1.80 V <sub>NHE</sub>	Acetonitrile	CO	H-cell	$j_{CO} = 11$	84	2 h	307
Cu/Ag(S)	Electrochemical treatment	-1.0 V <sub>RHE</sub>	0.1 M KHCO <sub>3</sub>	CO and C <sub>2</sub> + products	H-cell	$j_{ECO_2R} = 2.9$	93	1.5	308

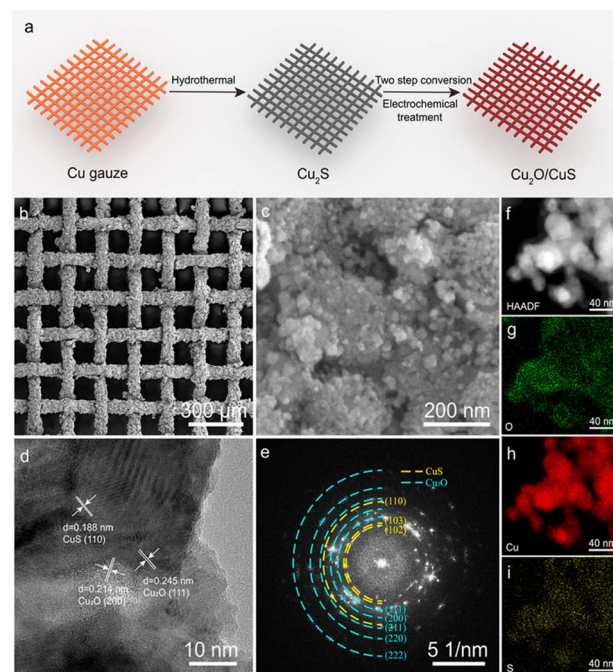


Fig. 2 (a) Schematic illustration of the synthesis of Cu<sub>2</sub>O/CuS nanocomposites. (b and c) SEM images of Cu<sub>2</sub>O/CuS nanocomposites grown on a copper gauze collected at different magnifications. (d) HR-TEM image collected from a representative Cu<sub>2</sub>O/CuS particle. (e) Corresponding FFT image of (d). Blue and yellow dashed lines highlight the diffraction rings of polycrystalline Cu<sub>2</sub>O and CuS particles, respectively. (f–i) HAADF-TEM image of Cu<sub>2</sub>O/CuS nanocomposites and the corresponding mapping images of elements O, Cu, and S (reprinted with permission from ref. 138. Copyright 2021, American Chemical Society).

selectivity. The use of sulfide-derived Cu with carbon catalysts can improve the efficiency of formate production in ECO<sub>2</sub>R. Furthermore, the substrate/catalyst interaction can also improve the ECO<sub>2</sub>R stability: Zhang *et al.*<sup>140</sup> synthesized multi-walled carbon nanotube (MWCNT) supported Cu<sub>1.81</sub>S catalyst through a simple two-step coupling strategy. The Cu<sub>1.81</sub>S@MWCNT-600 composite catalyst shown in Fig. 3g–j was accomplished with better ECO<sub>2</sub>R performance with a 30 h stability upon continuous operation owing to the highly active sites of homogeneously dispersed Cu<sub>1.81</sub>S particles (Fig. 3i) and efficient electron transfer and active sites granted by MWCNT. Later, they reported that oxide-modification Cu<sub>1.81</sub>S@MWCNT-600 (Cu<sub>1.81</sub>S@MWCNT-600-OD) exhibited better catalytic activity with a high FE<sub>Formate</sub> of 82%. The authors attribute this enhancement in electrocatalytic activity belongs to copper oxide compounds which undergo restructuring in a needle-like morphology and offer more active sites during electrolysis.

**2.1.2 Nanoscale engineering.** Since the electronic structure of the catalyst can be optimised by acting on the atomic and molecular organization, extensive research effort has been devoted to fine-tuning the nanoscale structure of MS-based nanomaterials, and a number of reviews<sup>141,142</sup> have detailed the modifications induced on the electronic structure and, consequently, the positive effects of this technique on

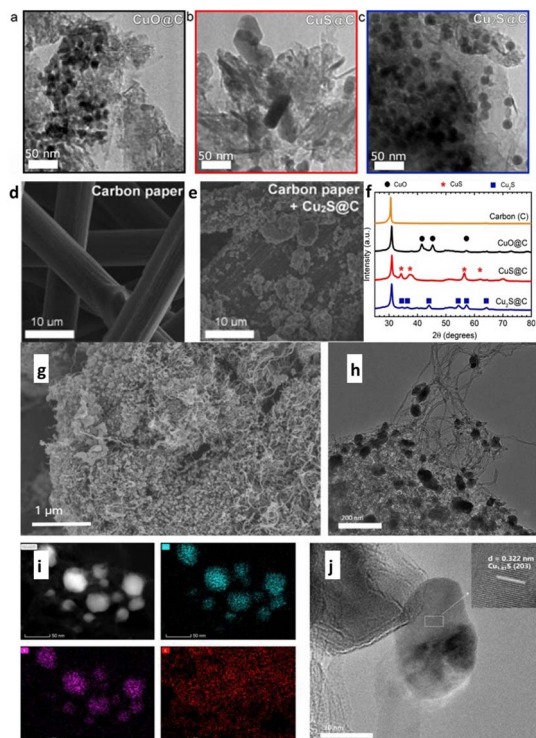


Fig. 3 TEM images of (a) CuO@C, (b) CuS@C and (c) Cu<sub>2</sub>S@C nanoparticles and corresponding particle size histograms, indicating an average particle size of  $9 \pm 3$  nm,  $25 \pm 13$  nm and  $17 \pm 1$  nm, respectively. SEM images of the carbon paper substrate (d) without any catalyst and (e) with Cu<sub>2</sub>S@C deposited on the carbon fibers by spraying. (f) X-ray diffractograms of the bare GNP-500 carbon support (orange) and of the CuO@C (black), CuS@C (red) and Cu<sub>2</sub>S@C (blue) nanoparticles on this carbon support. (Reprinted with permission from ref. 139. Copyright 2020, Elsevier); representative (g) SEM and (h) TEM micrographs of Cu<sub>1.81</sub>S@MWCNT-600, (i) HAADF-STEM image and corresponding EDS maps revealing the uniform distribution of Cu (blue), S (purple) in the Cu<sub>1.81</sub>S particles, and (j) HRTEM of Cu<sub>1.81</sub>S@MWCNT-600 (reprinted with permission from ref. 140. Copyright 2021, Elsevier).

electrocatalysis. The nanoscale engineering strategy enhances both the ECSA by maximizing the surface area to volume ratio and the intrinsic activity of the material because nanoscale effects like quantum confinement or plasmonic resonance modify the electronic structure at this length scale.<sup>143,144</sup>

For example, Shinagawa *et al.*<sup>145</sup> synthesized size-controlled carbon-supported nanometric CuS catalysts using the wet chemistry method. The experimental study revealed that synthesized nanometric CuS was further reduced to S-modified copper (Cu-S) catalysts during ECO<sub>2</sub>R. Therefore, S-modified copper (Cu-S) showed formate production (FE > 60%) with only trace amounts of CO at moderate overpotential ( $-0.8$  V vs. RHE). They observed that HCOOH generation enhanced slightly as particle size increased from 3 nm to 20 nm, which highlights the correlation between particle size and catalytic effect. Later on, in the same work, it was also shown that the submicron-sized CuS electrodes prepared *via* solvothermal method exhibited much higher FE<sub>HCOOH</sub> (80%) for electroreduction of CO<sub>2</sub> to HCOOH compared to the nanometric CuS electrodes

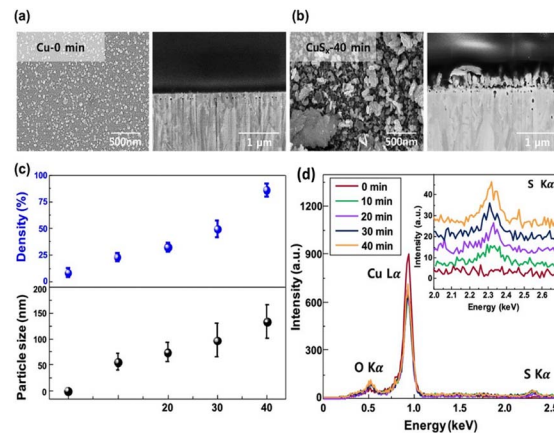


Fig. 4 Top-view and cross-sectional SEM images of (a) Cu-0 min without sulfur species and (b) CuS<sub>x</sub>-40 min catalysts. (c) Average particle size and surface density of CuS<sub>x</sub> NPs calculated by a computing-based image analyzer. (d) EDX spectra of Cu and CuS<sub>x</sub> catalysts (reprinted with permission from ref. 146. Copyright 2020, American Chemical Society).

(FE<sub>HCOOH</sub> > 60%), revealing the crucial role of particle size in enhancing catalytic activity. On the other hand, Lim *et al.*<sup>146</sup> examined the efficiency and product selectivity of a size-controlled CuS<sub>x</sub> catalyst prepared by dipping Cu foil in an industrial CO<sub>2</sub>-containing H<sub>2</sub>S in aqueous media. It was shown that the interaction between Cu foil and sulfur enhanced as the concentration of dissolved sulfur increased in an electrolyte (Fig. 4a and b). The simultaneous interaction increased the average particle size and surface sulfur density to  $133.2 \pm 33.1$  nm and  $86.2 \pm 3.3\%$ , respectively, for CuS<sub>x</sub> nanoparticles (NPs) (Fig. 4c and d). The FE<sub>Formate</sub> was also enhanced from 22.7 to 72.0% at  $-0.6$  V vs. RHE as the sulfur concentration and particle sizes of the CuS<sub>x</sub> NPs increase gradually. Although the CuS<sub>x</sub> catalysts showed less current density, the stability of 72 h must also be considered for converting industrial CO<sub>2</sub> to formate.

**2.1.3 Morphology and structure modification.** Modulating the morphology and structure of MS-based nanomaterials has always been a practical approach to optimizing catalytic performance and has achieved many outstanding research outcomes. By modulating the morphology and structure, the physicochemical properties of the promoter can be changed, thereby changing the catalytic activity and selectivity.<sup>147,148</sup> For example, it can effectively improve the active surface area of the catalyst, increase active sites for specific needs, generate novel and exciting physical phenomena, change the adsorption strength of the catalyst on the electrolyte or CO<sub>2</sub>, *etc.*<sup>70,72</sup>

Furthermore, this approach can tailor the microenvironments near the catalyst surface for target products. A study by Zhu *et al.*<sup>149</sup> showed that the Cu<sub>2</sub>S-modified Cu foam acts as an active electrocatalyst for CO<sub>2</sub> reduction in an H-cell setup. They deposited Cu<sub>2</sub>S nanoarrays on Cu foam *via* a two-step anodization method followed by heat treatment. In the first step, anodization occurred in an electrochemical cell where Cu foam worked as an anode and platinum foil as the cathode in an

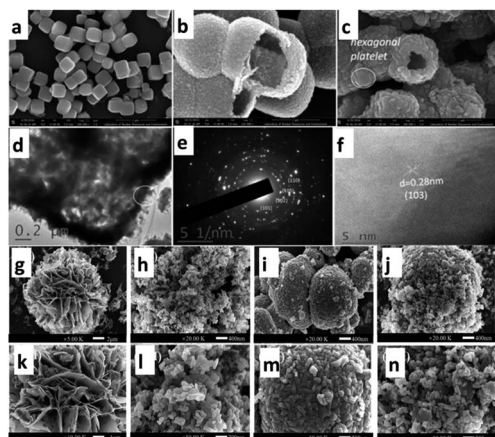


Fig. 5 SEM images of the samples (a–c): (a)  $\text{Cu}_2\text{O}$  MCs, (b)  $\text{h-Cu}_7\text{S}_4$  MCs, (c)  $\text{h-CuS}$  MCs. (d) TEM image of  $\text{h-CuS}$  MCs. (e) SAED patterns of the white circled region in (d). (f) HRTEM image of the  $\text{h-CuS}$  MCs. (Reprinted with permission from ref. 150. Copyright 2017, Elsevier). SEM of the different  $\text{CuS}$  catalysts. (g and h)  $\text{CuS-TU}$ , (i and j)  $\text{CuS-TAA}$ , (k and l)  $\text{CuS-STs}$ , and (m and n)  $\text{CuS-SS}$  at a low magnification and high magnification (reprinted with permission from ref. 151. Copyright 2023, American Chemical Society).

aqueous  $\text{Na}_2\text{S}$  solution. In the second step, the anodized copper foam was rinsed with distilled water and thermally treated. The synthesized three-dimensional (3D)  $\text{Cu}_2\text{S}/\text{Cu}$ -foam electrode exhibits significantly better  $\text{HCOOH}$  production (85% of  $\text{FECO}$  with  $j = 5.3 \text{ mA cm}^{-2}$  at  $-2.0 \text{ V vs. Ag/AgCl}$ ) than the  $\text{Cu}$ -foam electrode (maximum 38.9% of  $\text{FECO}$  at  $-1.8 \text{ V vs. Ag/AgCl}$ ). Shao *et al.*<sup>150</sup> reported  $\text{CO}_2$  reduction over hollow  $\text{CuS}$  microcubes (MCs) electrodes (Fig. 5a–c) and reported less overpotential. It was shown from Fig. 5d–f that as-prepared  $\text{h-CuS}$  MCs led to a higher density of defective edge exposed sites and are considered a key in the improved performance and stable selectivity ( $\text{FE}_{\text{CO}} = 32.7\%$  at a low onset potential  $-0.2 \text{ V vs. reversible hydrogen electrode}$ ). In 2023, Guo *et al.*<sup>151</sup> synthesized a series of  $\text{CuS}$  catalysts with various sulfur precursors *via* hydrothermal synthesis (Fig. 5g–n). Among all,  $\text{CuS}$ -thiourea exhibited superior  $\text{ECO}_2\text{R}$  activities compared to  $\text{CuS}$ -sodium thiosulfate,  $\text{CuS}$ -thioacetamide, and  $\text{CuS}$ -sodium sulfide  $\text{CO}_2$ -saturated  $0.1 \text{ M KHCO}_3$  electrolyte, high  $\text{CO}$  selectivity of 72.67% @  $-0.51 \text{ V vs. RHE}$ . The fast  $\text{S}$  decomposition of the thiourea precursor resulted in a higher  $\text{S}^{2-}$  concentration for faster nucleation rate and subsequent growth of unique nanoflower-shaped  $\text{CuS}$ -thiourea catalyst for facilitated mass transfer and favorable  $\text{ECO}_2\text{R}$  kinetics (Fig. 5g and h).

Later on, Zhao *et al.*<sup>152</sup> successfully synthesized efficient and stable  $\text{CuS}$  nanosheet arrays supported on nickel foam ( $\text{CuS@NF}$ ) substrate *via* a facile hydrothermal route for  $\text{ECO}_2\text{R}$  activity. The highly-dense  $\text{CuS}$  nanosheet is uniformly distributed on the  $\text{Ni}$  foam framework and forms a 3D hierarchical foam structure. The developed  $\text{CuS@NF}$  possessed highly open and porous structures with a thickness ranging from 20 to 25 nm. It was observed that modification with  $\text{S}$  species promotes  $\text{CO}_2$  adsorption and produces  $\text{CO}_2^{\cdot-}$  intermediate. Afterward, the  $\text{CO}_2^{\cdot-}$  intermediate reacts with  $\text{H}^+$  and  $\text{e}^-$  to

generate the  $\text{CH}_4$ . As a result, the  $\text{CuS@NF}$  obtained excellent  $\text{FE}_{\text{CH}_4}$  of 73.5% with a stability of 60 h for  $\text{CH}_4$  production with a high overpotential of  $-1.1 \text{ V vs. RHE}$ .

Chen and co-workers<sup>153</sup> prepared a series of differently structured copper sulfides using a simple ethylene glycol solvothermal process for  $\text{ECO}_2\text{R}$  to  $\text{HCOOH}$ . Then the group varied the morphology and composition of  $\text{CuS}$  nanoparticles by changing the  $\text{Cu/S}$  feed ratio and reaction temperature (Fig. 6a–f). Among all the synthesized  $\text{Cu}$ -rich nanoparticles,  $\text{CuS}$  nanoflowers exhibited the maximum  $\text{ECO}_2\text{R}$  performance with a significantly better  $\text{FE}_{\text{HCOOH}}$  of  $\sim 52\%$ . Likewise, Dou *et al.*<sup>154</sup> prepared  $\text{CuS}$  nanosheet arrays decorated on the brass mesh (BM) using a facile and energy-saving one-step chemical bath deposition process (Fig. 6g and h). Meanwhile, coupling of  $\text{CuS}$  with BM enhanced a large total current density up to  $75 \text{ mA cm}^{-2}$  at  $-0.7 \text{ V vs. RHE}$  with an  $\text{FE}$  of  $67.8 \pm 1\%$  for  $\text{HCOO}^-$  generation. But  $\text{CuS/BM}$  coated with PTFE obtained an  $\text{FE}$  of  $70.2 \pm 1\%$  for  $\text{HCOOH}/\text{HCOO}^-$  at  $-0.7 \text{ V vs. RHE}$ . Systematic studies show that a significant enhancement in catalytic reactivity was achieved through the restructuring of  $\text{CuS/BM}$  during the reduction process, resulting in a highly dispersed nanowire network with many active sites. They combined DFT studies with experimental observations. According to the study, excellent selectivity for  $\text{HCOO}^-$  generation was attributed to the reconstructed development of  $\text{Cu (111)}/\text{CuS (102)}$  facet during the reduction process. The theoretical study also indicates that  $\text{S}$  under the  $\text{Cu}^0$  layer was found to reduce the binding energies of  $\text{HCOO}^*$  and  $^*\text{COOH}$  on  $\text{Cu(111)}/\text{CuS(102)}$  compared to the

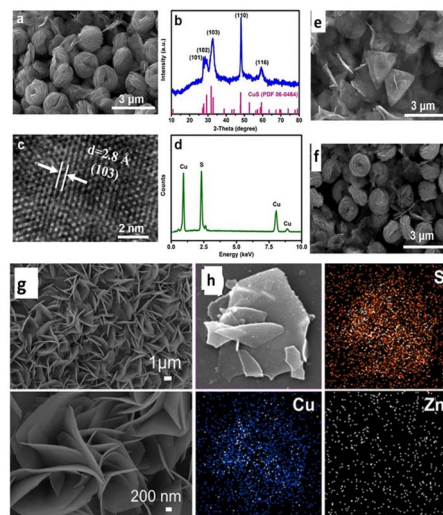


Fig. 6 (a) SEM image, (b) XRD pattern, (c) HR-TEM image, (d) EDX spectra of  $\text{CuS}$  nanoflowers synthesized at  $150 \text{ }^\circ\text{C}$  with  $\text{Cu/S}$  feed ratio of 1/3. (e) SEM image of  $\text{Cu}_{1.45}\text{S}$  nanoplates synthesized at  $150 \text{ }^\circ\text{C}$  with  $\text{Cu/S}$  feed ratio of 1/0.75; (f) SEM image of  $\text{Cu}_{1.54}\text{S}$  nanoflowers synthesized at  $180 \text{ }^\circ\text{C}$  with  $\text{Cu/S}$  feed ratio of 1/3. (Reprinted with permission from ref. 140. Copyright 2020, Elsevier); (g) SEM image of  $\text{CuS/BM}$ . (h) EDS mapping result of the  $\text{CuS}$  nanosheet for  $\text{S}$ ,  $\text{Cu}$ , and  $\text{Zn}$  elements (reprinted with permission from ref. 154. Copyright 2021, American Chemical Society).

Cu(111) plane, facilitating the production of HCOOH or HCOO\*.

In 2021 Zhang *et al.*<sup>155</sup> reported that MOF-derived hierarchical CuS hollow polyhedron (CuS-HP) structures effectively enhance ECO<sub>2</sub>R performance in neutral pH aqueous conditions. Their analysis showed that the CuS-HP is reduced into a sulfur-doped metallic Cu catalyst during catalysis. The durability of the *in situ* evolved catalyst observed a stable performance for 36 hours at a formate partial current density of 16 mA cm<sup>-2</sup> at -0.6 V vs. RHE with a faradaic efficiency of >90%. According to theoretical research, S-doping in the metallic Cu (111) facet does not change the reaction pathways but decreases the activation energy barriers for formate generation while suppressing HER. These works provide a clear understanding of enhancing HCOO<sup>-</sup> selectivity mechanisms for CuS electrode materials. Similarly, He *et al.*<sup>156</sup> studied the catalytic behavior of Cu<sub>2-x</sub>S derived polycrystalline Cu (Cu-S) catalyst for CO<sub>2</sub> conversion to C<sub>2</sub>H<sub>4</sub> formation. The nanostructured Cu-S catalysts exhibited better catalytic activity (FE of C<sub>2</sub>H<sub>4</sub> was 68.6% and partial current density of 40.8 mA cm<sup>-2</sup>) due to the high index facets during surface modification. *In situ* operando Raman techniques proved that the Cu-S catalysts follow the \*COCHO pathway to produce C<sub>2</sub>H<sub>4</sub> during the ECO<sub>2</sub>R process.

The modifications in electronic structure triggered by the surface modification can be fine-tuned to control the selectivity of the material for the desired electrocatalytic application against the competitive HER, Phillips and their team investigated the formate selectivity over copper electrodes derived from copper sulfide by *in situ* electro-reduction.<sup>157</sup> The surface-enhanced infrared absorption spectroscopy (SEIRA) observed that the S-derived Cu catalyst suppresses H<sub>2</sub> and CO generation while increasing the formate generation. The authors explain this improvement of formate selectivity *via* a plausible reaction mechanism: the CO<sub>ads</sub> tightly occupy some active catalytic sites, which interrupt the adsorbed hydrogen species (H<sub>ads</sub>) to combine and create an H<sub>2</sub> molecule. Therefore, H<sub>ads</sub> could only form H<sub>2</sub> in the solution phase by bonding protons *via* PCET. DFT calculations show that H<sub>ads</sub> might react with a CO<sub>2</sub> molecule in the solution phase instead of a solution containing H<sup>+</sup> to produce HCOOH. Thus, H<sub>ads</sub> intermediates adsorbed on S-derived Cu produced formic acid with solution-phase CO<sub>2</sub> through PCET.<sup>157</sup> In 2018, Deng *et al.*<sup>158</sup> compared ECO<sub>2</sub>R activity for active CuS<sub>x</sub> (AC-CuS<sub>x</sub>), desulfurized CuS<sub>x</sub> (DS-CuS<sub>x</sub>), and bare Cu catalysts (Fig. 7a-c). The AC-CuS<sub>x</sub> catalyst reported good selectivity and activity for formate synthesis (FE<sub>HCOO</sub> = 75% and *j*<sub>HCOO</sub> = 9.0 mA cm<sup>-2</sup> at -0.9 V<sub>RHE</sub>) compared to DS-CuS<sub>x</sub> (FE of 29.3%) and bare Cu (FE of 22.5%). The DFT analysis confirms that sulfur concentration reduces the adsorption strengths of HCOO\* and \*COOH, with \*COOH exhibiting less adsorption energy than HCOO\* (Fig. 7d-i). According to the findings, the high surface coverage of \*COOH intermediates occupies Cu sites surrounded by the sulfur atom, which thus interrupts electron transfer from those Cu sites to the intermediates (Fig. 7h and i). Therefore, the high amount of sulfur doping also weaker the adsorption of HCOO\*, which resulted in energy downhill of the rate-limiting step for formate production and increased its formation (Fig. 7e and f). Huang and the

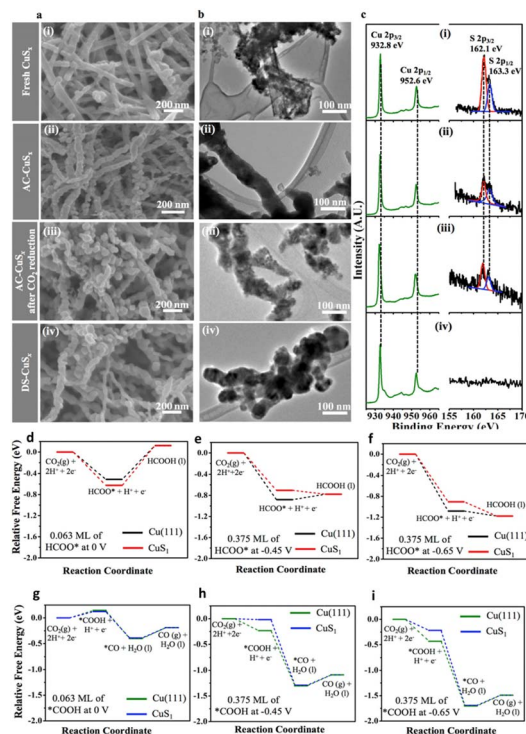


Fig. 7 (a) SEM images, (b) TEM images, and (c) XPS spectra of (i) fresh CuS<sub>x</sub> sample, (ii) AC-CuS<sub>x</sub> sample, (iii) AC-CuS<sub>x</sub> samples after 40 min of CO<sub>2</sub> reduction in 0.1 M KHCO<sub>3</sub> at -0.85 V vs. RHE, and (iv) DS-CuS<sub>x</sub> sample. Free energy diagrams of the HCOO\* pathways to formate on Cu (111) and CuS<sub>1</sub> surfaces at (d) 0 V and 0.063 ML (monolayer) of HCOO\*, (e) -0.45 V and 0.375 ML of HCOO\*, and (f) -0.65 V and 0.375 ML of HCOO\*. Free energy diagrams for \*COOH pathways to CO on Cu (111) and CuS<sub>1</sub> surfaces at (g) 0 V and 0.063 ML of \*COOH, (h) -0.45 V and 0.375 ML of \*COOH, and (i) -0.65 V and 0.375 ML of \*COOH (reprinted with permission from ref. 158. Copyright 2018, American Chemical Society).

group<sup>159</sup> prepared novel sulfur-doped Cu catalysts derived from Cu<sub>2</sub>O to give CO<sub>2</sub> to HCOOH. The authors observed that optimizing sulfur concentration is crucial in activating HCOOH production. Their study claimed that electrocatalyst (Cu-5000S) containing 2.7 atom% sulfur exhibits higher catalytic activity and formate selectivity (FE = 75% and *j* = -13.9 mA cm<sup>-2</sup> at -0.9 V vs. RHE). The mechanistic studies show that the sulfur-doped Cu lowers the binding strength of CO production intermediates COOH\*, which facilitates the production of HCOOH.

A novel electrochemically driven cation-exchange (ED-CE) technique introduced as a powerful method to systematically tune and modify the composition, morphology, and phase structure of a target nanocrystal (NC) assembly by a precise replacement of metal cations in a pre-designed NC template: He *et al.*<sup>160</sup> used ED-CE approach for obtaining highly active ECO<sub>2</sub>R copper sulfide catalysts. This synthesis method converted 3D-shaped CoS<sub>2</sub> into Cu<sub>2</sub>S with the novel 3-dimensional shape, although high grain boundaries were preserved (GBs), as illustrated in Fig. 8a. A ~87% faradaic efficiency (at -1.9 V<sub>RHE</sub> With a *j* = 19 mA cm<sup>-2</sup>) for CO<sub>2</sub> conversion to HCOOH was reported with the Cu<sub>2</sub>S nanocrystal electrode. Similarly, Jinghan Li *et al.*<sup>161</sup> incorporated ED-CE method that used copper sulfide as a growth

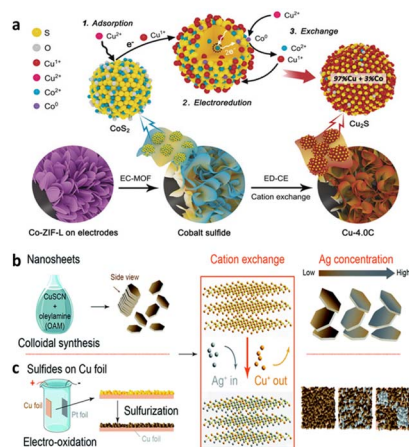


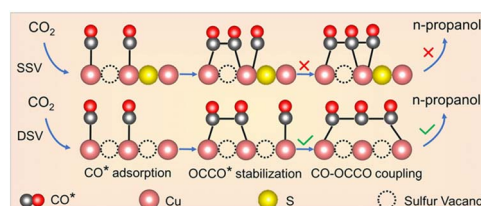
Fig. 8 (a) Schematic illustration of the experimental pathways and mechanisms for electrochemically driven cation exchange (ED-CE); synthetic strategies for Ag/Cu sulfide catalysts (reprinted with permission from ref. 160. Copyright 2020, John Wiley & Sons, Inc). (b) Cu sulfide nanosheets (C-nano-0, 100 nm lateral dimension, 14 nm thick) were obtained through colloidal synthesis with CuSCN in oleylamine (OAM). (c) Cu sulfides on Cu foil (C-foil-x) were obtained through electrooxidation in 1 M NaOH to produce an oxide layer of a few 10 s of microns thick, followed by sulfurization with 0.1 M Na<sub>2</sub>S. After cation exchange where Ag<sup>+</sup> replaces the Cu<sup>+</sup> in the Cu sulfides, Ag/Cu sulfide nanosheets (CA-nano-x) remain nanosheet structure with some distortion in shape as the Ag/Cu mass ratio ranges from 0.3 to 25; while for C-foil-x, Ag nucleates at higher Ag concentration, that impedes the uniform distribution of Ag and Cu (reprinted with permission from ref. 161. Copyright 2021, The Royal Society of Chemistry).

template to synthesize Ag/Cu bimetallic catalysts for ECO<sub>2</sub>R (Fig. 8b and c). They used Cu<sub>2-x</sub>S nanosheets (denoted as C-nano-0 with a lateral dimension of 100 nm and 14 nm thick) as a precursor. It was observed that during synthesis increasing Ag<sup>+</sup> concentration (by changing Ag/Cu mass ratio ranges from 0.3 to 25) in the exchange solution possesses a steady shift in crystal structures from Cu<sub>7</sub>S<sub>4</sub> to Ag<sub>2</sub>S (CA-nano-x, where x denotes higher Ag concentration). Therefore, both C-nano-0 and cation-exchanged nanosheets showed extremely good FE<sub>HCOOH</sub> at a low overpotential (−0.2 V vs. RHE). Surprisingly, the Ag combination enhanced the generation of C<sub>2+</sub> products at −1.0 V vs. RHE compared to C-nano-0, which mainly generates formate. In the next step, Cu sulfides to a depth of a few 10 s of microns were deposited using a two-step electrooxidation/sulfurization on Cu foil (C-foil-x). They observed that cation exchange creates evenly dispersed Ag at lower Ag<sup>+</sup> concentrations; however, at higher Ag<sup>+</sup> concentrations, Ag particles nucleate on the surface. Their findings show that the production of ethylene and methane initially increased with time for silver/copper sulfides on Cu foil (CA-foil-x-y). Later, it decreased as H<sub>2</sub> evolution occurred, and the catalyst's shape evolved towards a nest-like structure with a diameter of 20 nm, which could explain the change in selectivity. This result is due to the ED-CE process, which modified uncoordinated sites, crystal phase structure, composition, and density, enabling the construction of additional active sites for ECO<sub>2</sub>R catalysis.

**2.1.4 Defects engineering.** Theoretical and experimental studies revealed the possibility of tuning the electronic structure by introducing defects (*i.e.*, chalcogen or distortion in the material's lattice). Introducing defects and distortion is the most investigated technique employed to activate the otherwise inert basal plane. The primary role of the vacancy sites has been comprehensively studied in the literature:<sup>162–164</sup> the missing chalcogen atom exposes the underlying metal surface, whose dangling bonds states of the d-orbital are responsible for the creation of the gap states near the Fermi level, with an energy reaching that of the Fermi level as the chalcogen vacancy percentage increases. These gap states can hybridize with the orbitals of the reactant, thus favoring their adsorption and improving the catalytic activity of the material.

A shift in selectivity can be obtained by employing S-vacancy metal sulfide-based catalysts, where CO<sub>2</sub> can be transformed into value-added C<sub>2+</sub> products. Zhuang and colleagues<sup>165</sup> demonstrated that incorporating sulfur atoms in the catalyst core and copper vacancies in its shell present excellent ECO<sub>2</sub>R activity. The bifunctional Cu<sub>2</sub>S–Cu–V (V denotes vacancy) electrocatalyst consists of S atoms in the nanoparticle core and copper vacancies in the shell with high electron density. The Cu<sub>2</sub>S–Cu–V catalyst exhibited excellent electrochemical activity by generating C<sub>2+</sub> alcohols (*i.e.*, C<sub>3</sub>H<sub>7</sub>OH and CH<sub>3</sub>CH<sub>2</sub>OH) with a faradaic efficiency of 32% ± 1%. Compared to simple copper nanoparticles, the alcohol-to-ethylene ratio increased six times, suggesting an alternate path for alcohol production rather than alkenes. DFT simulations revealed that core–shell vacancy engineering increases the energy barrier of the C<sub>2</sub>H<sub>4</sub> route (1.148 eV) but has no effect on the CH<sub>3</sub>CH<sub>2</sub>OH path (0.427 eV). Peng *et al.*<sup>166</sup> investigated the roles of double-sulfur vacancies (DSV) structure in ECO<sub>2</sub>R. It was shown that the DSV in CuS<sub>x</sub> enabled the stability of both CO\* and a \*C<sub>2</sub> dimer (*i.e.*, OCCO\*), with a subsequent coupling with a third \*CO through CO–OCCO, as depicted in Scheme 1. The DSV-rich CuS<sub>x</sub> showed an enhanced FE<sub>n-PROH</sub> of ~15.4% for *n*-propanol generation at −1.05 V<sub>RHE</sub> in 0.1 M KHCO<sub>3</sub> in the H-cell configuration.

**2.1.5 Interfacial engineering.** Interface engineering is an essential strategy for modulating electrocatalytic activity. Interfaces enable rapid charge transfer and modified free energies of intermediates due to the strong interfacial interactions between components.<sup>167</sup>



Scheme 1 Schematics of CuS<sub>x</sub> with double sulfur vacancies for converting CO<sub>2</sub> to *n*-propanol, and the corresponding calculations. A Mechanism of *n*-propanol formation on adjacent CuS<sub>x</sub>-DSV, showing the dimerization of CO–CO followed by CO–OCCO coupling (reprinted with permission from ref. 166. Copyright 2021, Nature Publishing Group).

Constructing bridging bonds at the interface to form strongly coupled hybrid catalysts can significantly increase the  $\text{ECO}_2\text{R}$  activity. For example, Wang *et al.*<sup>168</sup> synthesized novel hierarchical 0D/2D heterostructures of  $\text{SnO}_2$  nanoparticles confined on  $\text{CuS}$  nanosheets ( $\text{SnO}_2/\text{CuS}$  NSs) for syngas production with a ratio tuned of 0.11–3.86 ( $\text{CO}/\text{H}_2$ ). Their catalytic system was found to be highly selective for syngas production with a FE of >85%, a turnover frequency (TOF) value of  $96.12 \text{ h}^{-1}$ , and long-term stability of 24 hours. The authors explain this higher catalytic activity for two reasons: (a) the uniformly dispersed ultrasmall  $\text{SnO}_2$  nanoparticles on ultrathin  $\text{CuS}$  nanosheets provide the highest number of active sites, which allow a faster rate of electron transfer; and (b) the distinct  $\text{SnO}_2$  and  $\text{CuS}$  interfaces reduce the activation energy of reaction intermediates, thus improving  $\text{ECO}_2\text{R}$  activity to produce high-ratio tunable syngas. The DFT study revealed that individual  $\text{SnO}_2(110)$  and  $\text{CuS}(001)$  surfaces favored  $\text{HCOOH}$  generation, but in this case,  $\text{SnO}_2/\text{CuS}$  interface significantly reduced free energy of 0.52 eV for  $\text{COOH}^*$  intermediate formation and promoted  $\text{CO}$  formation.

Modulating and understanding the intermediates that form on the surface of an electrocatalyst during  $\text{ECO}_2\text{R}$  is vital to overcome limitations associated with the adsorption of  $\text{CO}_2$  molecules. Han *et al.*<sup>169</sup> constructed an intermetallic ternary  $\text{Bi-Cu}_2\text{S}$  heterostructure catalyst prepared by the one-pot solution-phase method. Owing to the strong chemical interaction effects between  $\text{Bi}$  and  $\text{Cu}_2\text{S}$  and its unique heterostructure, it attained a reduced overpotential (240 mV lower than  $\text{Bi}$ ) and an exceptional FE (>98%) for formate generation with a high partial current density (2.4 and 5.2 times more  $-J_{\text{HCOO}}$  than bare  $\text{Cu}_2\text{S}$  and  $\text{Bi}$  at  $1.0 V_{\text{RHE}}$ ). Mechanisms study demonstrated that the higher rate of electron transfer from  $\text{Bi}$  to  $\text{Cu}_2\text{S}$  at the interface preferentially stabilizes the  $^*\text{OCHO}$  intermediates over  $^*\text{COOH}$  and  $^*\text{H}$ , which facilitates  $\text{HCOOH}$  formation. Similarly, Xiong *et al.*<sup>170</sup> synthesized bimetallic  $\text{CuInS}_2$  hollow nanoparticles with a homogeneous mixing procedure. The combined benefits of the synergistic effect of the metal center and hollow nanostructures resulted in faster electron transfer. As a result, the bimetallic catalyst achieved a  $\text{FE}_{\text{CO}}$  of 82.3% at  $-1.0 V_{\text{RHE}}$ , while  $\text{FE}_{\text{HCOOH}}$  was 72.8% at  $-0.7 V_{\text{RHE}}$ . *In situ* Raman spectroscopy revealed that  $\text{CO}_2$  was activated to  $\text{CO}_2^{*-}$  intermediates, and electron redistribution occurred under differing potentials, resulting in a change in product distribution ( $\text{CO}$  to  $\text{HCOOH}$ ). In addition, according to Nyquist plots,  $\text{CuInS}_2$  hollow nanostructures have a significantly higher charge-transfer rate during the  $\text{CO}_2$  reduction reaction because their interfacial charge-transfer impedance ( $R_{\text{ct}}$ ) is lower than that of  $\text{Cu}_2\text{In}$ .

In another effort to modulate interfacial charge distribution and promote  $\text{CO}_2$  adsorption, Wen and co-workers proposed a robust technique based on local sulfur doping of a Cu-based metal-organic framework precatalyst and stable Cu-S motif distributed throughout the HKUST-1 framework (denoted as S-HKUST-1). The regenerative catalysts matrix exhibits a high  $\text{C}_2$  product ( $\text{C}_2\text{H}_4$ ) selectivity of up to 57.2% at the operated current density of  $400 \text{ mA cm}^{-2}$ . For  $\text{ECO}_2\text{R}$  catalysis, this is the best selectivity and activity value for  $\text{C}_2\text{H}_4$  among the Cu-based metal-organic species and MOFs. The operando XAFS

investigation and systematic characterizations depicted that the Cu-S motif is stable during the process and stabilizes more active  $\text{Cu}^{\delta+}$  species. The authors rationalize the excellent selectivity of S-HKUST-1 compared to copper or copper sulfide as follows: the approximate  $\text{Cu}^0\text{-Cu}^{\delta+}$  distance was favorable for the  $^*\text{CO}$  dimerization step at the  $\text{Cu}/\text{Cu}_2\text{S}$  interface. Moreover, an extremely high S-content catalyst (*i.e.*,  $\text{Cu}_2\text{S}$ ) exhibited a long Cu-Cu distance, which hindered  $^*\text{CO}$  dimerization geometrically; the  $\text{Cu}/\text{Cu}_2\text{S}$  interface offered lower binding energy to  $^*\text{CO}$  species in rising to  $^*\text{CO}$  dimerization than a pure metallic Cu catalyst.<sup>171</sup>

## 2.2 Cadmium (Cd)-based sulfide

Cadmium sulfide (CdS) is a low-cost II-VI group semiconductor material with a narrow bandgap energy of 2.42 eV. Because of its inexpensive cost, variety of polymorphs, and outstanding optical/electronic properties, it has been extensively explored for solar energy applications. The above-mentioned inherent characteristics of CdS make it suitable for photochemical and electrochemical water-splitting, photochemical  $\text{CO}_2$  reduction, *etc.* Several strategies, such as heterojunction formation, co-catalyst loading, and heteroatom doping, are being reported.<sup>172–174</sup> Among all, doping heteroatoms in CdS have proven to be a very useful technique because it manipulates the intrinsic electronic structure and revises the Fermi energy level. It also unveils some impurity levels between the conduction band maximum and the valence band maximum, which are normally electron trapping centres.<sup>175</sup> For example, Ag material has been chosen for doping because it has excellent electrical and thermal conductivity and is also ideal for electrical applications.<sup>176</sup> In some recent studies, CdS is doped with two or more reactants as precursors, with the goal of overcoming the difficulty of modulating electronic configuration and nanostructures due to the multi-component reaction.<sup>177,178</sup> Some promising findings for CdS-based hybrids with various materials for various applications have been reported such as photocatalytic and electrocatalytic water splitting, photocatalytic  $\text{CO}_2$  reduction, photoelectrochemical water splitting, and it is also used in solar cells.<sup>179–181</sup> This section will discuss current advancements in CdS-based electrocatalysts for  $\text{CO}_2$  reduction in terms of their morphological structures, doping, vacancies, and electrode surface modification.

**2.2.1 Morphology and structure modification.** Apart from the inherent properties of electrocatalysts, the surface morphology also plays a crucial role in tailoring the efficiency of electrocatalytic  $\text{CO}_2$  reduction. Since the superior accessibility of porous configuration with gas molecules, it is notably important to design porous electrocatalysts for the improvement of  $\text{CO}_2$  adsorption and efficiency of  $\text{ECO}_2\text{R}$ .<sup>182</sup> Sulfur atoms attachment of an electrocatalyst to amorphous and porous Cadmium (Cd) support (P-CdS) has been shown to selectivity shift from  $\text{HCOOH}$  to  $\text{CO}$  as demonstrated by Wu *et al.*<sup>183</sup> in which  $\text{Cd}^{2+}$  cations were tetrahedrally coordinated with  $\text{S}^{2-}$  anions *via* covalent orbital hybridizing s and p bands (Fig. 9a–g). They reported the DFT study, as shown in Fig. 9h–l. According to this finding, the hybridized sp band of CdS

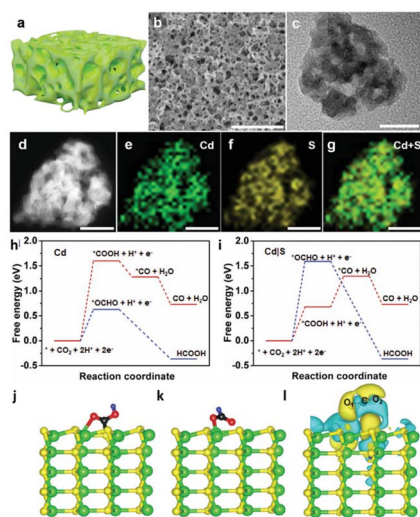
systems adsorbs  $\text{CO}_2$  to generate  $^*\text{COOH}$  intermediate, which accelerates CO formation.

Furthermore, Gao *et al.*<sup>184</sup> reported that a high-curvature CdS nanosized catalyst has a significant proximity effect that results in massive electric field amplification, which may concentrate alkali-metal cations. They synthesized a series of CdS nanoparticles (*i.e.*, nanoneedles, nanorods, and nanoparticles) with various tip radii by taking different reactant quantities using a microwave heating strategy (Fig. 10a–d). They detected that the tip-concentrated electric fields rise tenfold at  $-1.0$  V as the tip stiffens from a radius of 24 nm to 3 nm (Fig. 10d and e). However, Gao *et al.* also found that the concentration of  $\text{K}^+$  adsorbed on the surface of the CdS tip increased by 114-fold due to the highly concentrated electric field. The finite-element method simulations revealed that CdS needles in close proximity could further restrict electric fields that offer influence in  $\text{K}^+$  concentrations. They also exhibited that gap width decreases with increasing  $\text{K}^+$  concentration distribution because of the higher electric field inside the nanogap (Fig. 10f and g). Therefore, it is well established that  $\text{K}^+$  ions interact with  $\text{CO}_2$  through a non-covalent effect; that facilitates fast  $\text{CO}_2$  stabilization at the CdS needle tips and nanogaps, where  $\text{CO}_2$  reduction occurs. As a result, CdS nanoneedle exhibited excellent faradaic efficiency above 90% at  $-1.2$   $V_{\text{RHE}}$  with a current density of  $212$   $\text{mA cm}^{-2}$ . Gao and his group conducted a 24 hours extreme stability test on CdS needles at  $1.0$   $V_{\text{RHE}}$  in  $0.1$  M  $\text{KHCO}_3$ . Notably, the findings reveal a steady  $\text{FE}_{\text{CO}}$  of over 90% with a low current density decay. This work enables  $\text{ECO}_2\text{R}$  by creating a catalyst

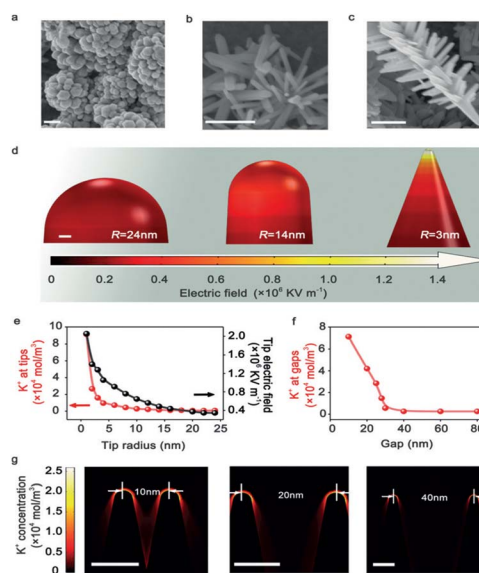
structure that adsorbs more electrolyte cations, stabilizing the intermediates.

Although  $\text{H}_2$  is considered a “by-product” in the majority of cases of  $\text{ECO}_2\text{R}$ , and several strategies have been implemented to reduce the HER, its formation is not entirely meaningless. This is because  $\text{H}_2$  and CO are the two main syngas components required in various industrial processes. He and co-workers<sup>185</sup> investigated a series of cadmium sulfoselenide ( $\text{CdS}_x\text{Se}_{1-x}$ ) nanorods for the  $\text{ECO}_2\text{R}$  to syngas selectivity. The synthesized electrocatalyst enabled a broad range of syngas proportions and observed a higher current density above  $10$   $\text{mA cm}^{-2}$ . In addition,  $\text{CdS}_x\text{Se}_{1-x}$  nanorods exhibited an 81% faradaic efficiency with a current density of  $27.1$   $\text{mA cm}^{-2}$  for CO production. The experiment also showed that the faradaic efficiency for  $\text{H}_2$  emission increases at  $-1.2$   $V_{\text{RHE}}$  when Se content increases in  $\text{CdS}_x\text{Se}_{1-x}$  nanorods. The mechanistic study revealed that the higher Se percentage in  $\text{CdS}_x\text{Se}_{1-x}$  nanorods improved H atoms binding to the catalyst surface and resulted in increasing  $\text{H}^*$  surface coverage, subsequently enhancing HER in  $\text{ECO}_2\text{R}$ .

**2.2.2 Defect engineering.** The incorporation of defects ( $\text{S}_v$  vacancy,  $\text{S}_v$ ) in sulfide electrocatalysts can be a promising approach for tuning the adsorption energy of the key intermediates to improve the catalytic reaction kinetics.<sup>186</sup> Theoretical findings have confirmed that the surface  $\text{S}_v$  is crucial for the  $\text{ECO}_2\text{R}$  because of the appropriate binding energy of COOH to desorb the CO product further. Additionally,  $\text{S}_v$  can increase the



**Fig. 9** (a) Schematic diagram of porous structure of P-Cd|S. The morphology of P-Cd|S characterized by (b) SEM, (c) TEM, and (d–g) HADDF-STEM. Scale bars are (b) 500 nm and (c–g) 100 nm. Gibbs free energy diagrams of (h) Cd metal, (i) sulfur-modified Cd. Optimized adsorption configuration of (j)  $^*\text{COOH}$  and (k)  $^*\text{OCHO}$  intermediates. (l) Differential charge density of  $\text{CO}_2$  adsorbed on Cd|S, regions of yellow and cyan denote electron accumulation and depletion, respectively. Green, yellow, black, red, and blue balls represent Cd, S, C, O, and H atoms, respectively (reprinted with permission from ref. 183. Copyright 2020, John Wiley & Sons, Inc).



**Fig. 10** (a)–(c) SEM images of CdS particles (a) rods (b) and needles (c). Scale bars, 400 nm. (d) Electric field on the surface of different catalysts is shown as a color map. The tip radius of the structure in each panel is 24 nm (left), 14 nm (middle), and 3 nm (right). Scale bar, 5 nm. (e) Adsorbed  $\text{K}^+$  and the electric field intensity at the tip, revealing that both adsorbed  $\text{K}^+$  and electrostatic field intensity increase as the tip radius decreases. (f)  $\text{K}^+$  concentration intensity in the CdS needle gap increases as the gap distance decreases. (g)  $\text{K}^+$  concentration distribution in the needle gap, showing enhanced  $\text{K}^+$  concentration in the narrow gap. Scale bars from left to right: 10 nm, 10 nm, and 15 nm (reprinted with permission from ref. 184. Copyright 2020, John Wiley & Sons, Inc).

carrier concentration, enhancing charge transfer during the  $\text{ECO}_2\text{R}$ .<sup>187–189</sup> However, quantitative and continuous engineering of  $S_V$  content in CdS nanorods for  $\text{CO}_2$  reduction has only received sporadic attention. More research is needed to gain a better understanding of the surface  $S_V$  contents and their effects on electrocatalytic properties.

Li *et al.*<sup>190</sup> developed simple cadmium sulfide (CdS) nanorods for  $\text{ECO}_2\text{R}$  to CO. The presence of (0002) surface with  $S_V$  in CdS nanorod increases the performance (95% FE with  $j_{\text{CO}}$  of  $-10 \text{ mA cm}^{-2}$  at an overpotential of  $-0.55 V_{\text{RHE}}$ ) and selectivity toward CO formation. Elsewhere, bulk CdS particles with size in micron level exhibited 60% selectivity for CO production in 0.5 M  $\text{KHCO}_3$  at a potential of  $-0.9 V_{\text{RHE}}$ . The absence of (0002) face in CdS nanorods decreases the performance and selectivity toward CO formation. An  $\text{ECO}_2\text{R}$  to CO with low overpotential utilizing the cadmium sulfide (CdS) catalyst with  $S_V$  was studied by Li *et al.*<sup>191</sup> They observed that CdS nanorods were mainly exposed to the (002) face with sulfur vacancies, suppressing HER while increasing CO selectivity. Theoretical work confirmed that the (002) plane with a medium concentration of  $S_V$  showed better catalytic activity than without  $S_V$  due to the higher binding energy of  $^*\text{COOH}$  intermediates. They also identified that CdS nanorods with a medium (9%) surface  $S_V$  resulted in better faradaic efficiency and catalytic activity. Qin *et al.*<sup>192</sup> reported the  $\text{CO}_2$  electrochemical reduction for cadmium sulfide-supported carbon nanotubes composite catalyst (CdS-CNTs) (Fig. 11a–j) synthesized by a simple solvothermal approach. The composite material produced CO with a FE of more than 95%. Subsequently, the group explored the surface electron density of cadmium sulfide with  $S_V$  and the energy required for CO formation (Fig. 11k–s). The *in situ* infrared absorption spectroscopy with attenuated total reflection mode (ATR-IRAS) was used to evaluate the intermediate species formed during the process in order to detect the surface reaction on CdS-CNTs (Fig. 11k–n). As illustrated in Fig. 11m, it was observed that  $\text{CO}_2$  adsorption above the CdS-CNTs surface increases after the electrode is electrified. Next, the area around Cd exhibits less blue in the presence of  $S_V$  than in the Cd without  $S_V$ , which signifies that the negative charge is partially transferred to Cd when  $S_V$  are created (Fig. 11o and p). DFT calculation proposed that  $S_V$  in CdS(111) increase the electron density on the catalyst surface and lower the energy required for  $\text{COOH}^*$  to  $\text{CO}^*$  conversion, facilitating the electro-reduction of  $\text{CO}_2$  to CO (Fig. 11q–s).

In recent years, a new 2D material, MXene, emerged comprising transition metal carbides, nitrides, and carbonitrides.<sup>193,194</sup> These breakthrough materials are developed from three-dimensional (3D) ternary ceramic material MAX (M = transition metal, A is an A-group which is typically IIIA and IVA, or groups 13 and 14 components in the periodic table, and X is carbon/or nitrogen). MXene-based sulfides materials have been widely used as a substrate to prepare electrocatalysts for HER, nitrogen reduction reaction, oxygen reduction, or evolution reaction (ORR/OER) due to their 2-D structure, hydrophilic nature, excellent electrical conductivity, and richness of surface functional groups.<sup>195–197</sup> In 2021, Wang *et al.*<sup>198</sup> adopted a simple solvothermal approach to design a series of CdS and  $\text{Ti}_3\text{C}_2$

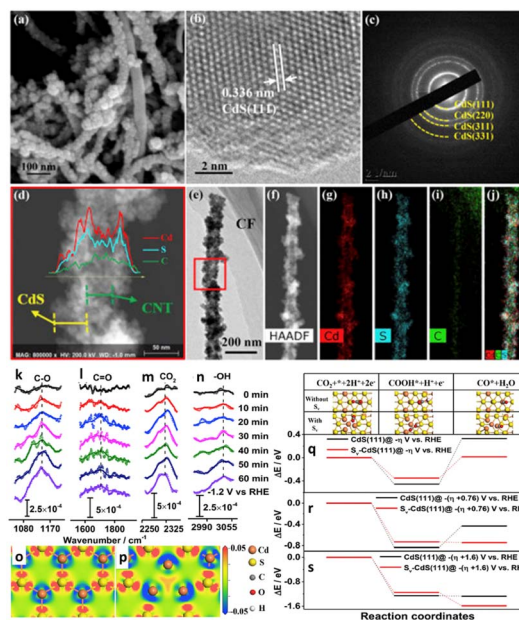


Fig. 11 (a) FESEM image of CdS-CNTs; HRTEM images of CdS-CNTs: (b) interplanar lattice fringe spacing, (c) SAED pattern, (d) line scan, (e) HRTEM image, (f–j) HAADF-STEM and elemental mapping; (k–n) *In situ* ATR-IRAS analyses of CdS-CNTs for  $\text{ECO}_2\text{R}$ . The distribution of electron deformation density: (o) CdS(111) without S-vacancy and (p) CdS(111) with S-vacancy. (q–s) DFT calculation results of relative energy for possible intermediates during  $\text{CO}_2\text{RR}$  on CdS(111) without S-vacancy and CdS(111) with S vacancy ( $S_V$ ) at different potentials (reprinted with permission from ref. 192. Copyright 2019, Elsevier).

MXene composites followed by  $\text{H}_2/\text{Ar}$  treatment, as shown in Fig. 12a. Uniform hierarchical structures of CdS nanoparticles with abundant sulfur vacancies dispersed in the  $\text{Ti}_3\text{C}_2$  MXene matrix were observed by the SEM, HRTEM, and TEM (Fig. 12b, e, f and g). DES elemental mappings and XRD analysis confirmed the presence of the Cd, S-vacancies ( $V_S$ ), Ti, and C (Fig. 12c and d). The 2D MXene skeleton structure accelerates electrolyte absorption, enables rapid electron transport, and increases electrochemical surface area. Because of these advantages, *i.e.*, high catalytic activity and electrical conductivity,  $V_S\text{-CdS}/\text{Ti}_3\text{C}_2$  has faster  $\text{CO}_2$  electroreduction reaction kinetics and achieved a  $\text{FE}_{\text{CO}}$  as high as 94% at  $-1.0 V$  vs. RHE (Fig. 12h–k). The group suggested that the HER activity of the composite materials can be regulated by regulating the surface exposed Ti element concentration. This study builds the foundation for developing MXene-based composite electrocatalysts for  $\text{ECO}_2\text{R}$  in aqueous solutions.

**2.2.3 Interfacial engineering.** Constructing metal sulfide/metal sulfide heterojunctions is an effective strategy to create interfaces in MS-based electrocatalysts. For instance, combining  $\text{Ag}_2\text{S}$  nanodots with CdS nanorods showed excellent electrical conductivity and chemical stability during  $\text{ECO}_2\text{R}$ . Compared to separately synthesized bare CdS ( $j = 9.5 \text{ mA cm}^{-2}$ ) and  $\text{Ag}_2\text{S}$  ( $j = 5.5 \text{ mA cm}^{-2}$ ),  $\text{Ag}_2\text{S}/\text{CdS}$  electrocatalyst showed a higher partial current density of  $10.6 \text{ mA cm}^{-2}$  at  $-1.1 V$  vs. RHE for CO selectivity. They exhibited higher faradaic efficiency of 97% with a current density range of 80 to  $200 \text{ mA cm}^{-2}$  for



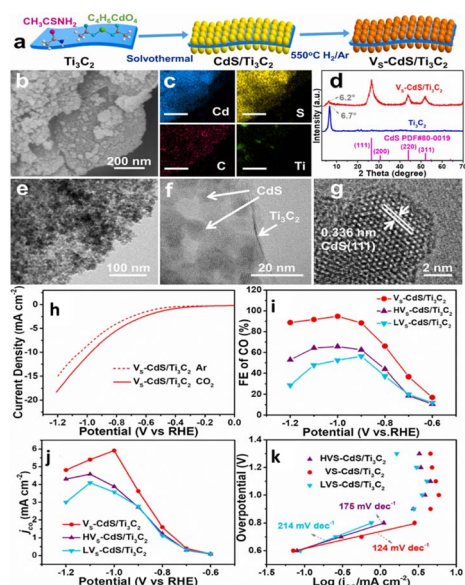
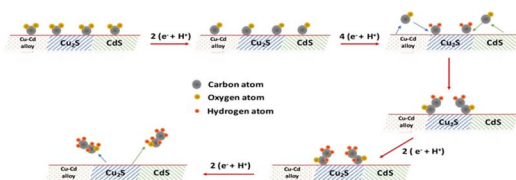


Fig. 12 (a) Schematic illustration for the preparation of  $V_5$ -CdS/ $Ti_3C_2$ . (b) SEM image and (c) DES elemental mapping images (scale bar, 5  $\mu$ m) of  $V_5$ -CdS/ $Ti_3C_2$ . (d) XRD patterns of CdS,  $Ti_3C_2$  and  $V_5$ -CdS/ $Ti_3C_2$ . (e and f) TEM and (g) HRTEM images of  $V_5$ -CdS/ $Ti_3C_2$ . (h) LSV curves of  $V_5$ -CdS/ $Ti_3C_2$  in  $CO_2$  (solid line) and Ar (dash line) saturated 0.1 M  $KHCO_3$  aqueous solution. (i) FE for CO, (j) partial current density (CO) and (k) Tafel plots of  $LV_5$ -CdS/ $Ti_3C_2$ ,  $V_5$ -CdS/ $Ti_3C_2$  and  $HV_5$ -CdS/ $Ti_3C_2$  (reprinted with permission from ref. 198. Copyright 2021, Elsevier).

formate and CO production when  $ECO_2R$  was employed in a flow cell. Compared to other loadings (2 wt%, 8 wt%, 10 wt%), the  $CO_2$  reduction activity was found best at 5 wt%  $Ag_2S$  loading on the surface of the CdS nanorods.<sup>199</sup>

Designing catalysts with multiple active sites for synergistic  $CO_2$  adsorption and activation of key intermediates, can significantly accelerate multicarbon chemicals (mainly ethanol) generation and inhibit the undesired HER. As reported, the conversion of  $ECO_2R$  to ethanol needs C-C coupling, which may be accomplished by fulfilling two conditions: first, sufficient carbon species at the catalyst surface for the coupling stage; second, stabilization of  $C_2$  intermediates across the catalyst surface for the further reduction process.<sup>200</sup> In this context, Mosali *et al.*<sup>201</sup> prepared sulfide-derived copper-cadmium catalysts SD-Cu<sub>x</sub>Cd<sub>y</sub>, where x and y denote Cu to Cd molar ratio to facilitate the formation of crucial intermediates. The SD-CuCd<sub>2</sub> catalyst achieved a FE of ethanol production of ~32% at a low



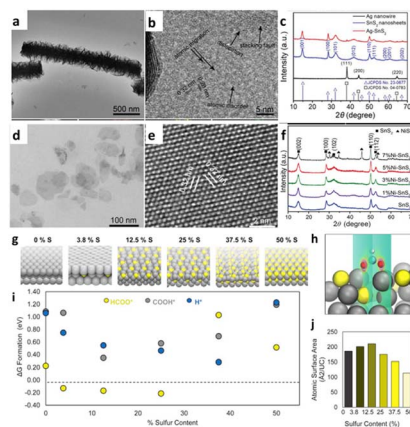
Scheme 2 Proposed mechanism for the formation of  $CH_3CH_2OH$  at SD-CuCd<sub>2</sub> catalyst – Cu–Cd alloy/ $Cu_2S$ /CdS phase boundaries (reprinted with permission from ref. 201. Copyright 2021, John Wiley & Sons, Inc).

overpotential of 0.89  $V_{RHE}$  in 0.1 M  $KHCO_3$  solution. They found ethanol was the only formed  $C_2$  product at low reduction potentials with the best-performed SD-CuCd<sub>2</sub> catalyst containing  $Cu_3Cd_{10}$  alloy/ $Cu_2S$ /CdS phase boundaries. The reaction mechanism is also described in detail, as shown in Scheme 2.

### 2.3 Tin (Sn)-based sulfide

Tin sulfides are composed of many binary compounds, including SnS,  $Sn_2S_3$ ,  $Sn_3S_4$ ,  $Sn_4S_5$ , and  $SnS_2$ .<sup>202,203</sup> Among these compounds, SnS and  $SnS_2$  are the most important and have attracted the greater interest of researchers due to their remarkable features and potential uses in energy storage systems.<sup>204–208</sup> Meanwhile, numerous SnS nanostructured with various morphologies, including nanoparticles,<sup>209</sup> nanorods,<sup>210,211</sup> nanoneedles,<sup>212</sup> rectangular nanosheets,<sup>213</sup> nanoflowers,<sup>214</sup> and core-shell nanospheres<sup>215</sup> have gained considerable interest for energy applications. Similarly, several  $SnS_2$  nanomaterials, such as ultralong nanobelts,<sup>216</sup> hexagonal nanoplates,<sup>217–220</sup> nanosheets,<sup>221</sup> and 3D-hierarchical spheres/flowers modified by nanoplates/nanosheets<sup>222–224</sup> have been exhibited as high electrocatalytic activity. In this section, with a focus on Sn-based sulfides, we present the most popular design strategies for these materials with the goal of enhancing their  $ECO_2R$  catalytic performance by changing the structural and electrical properties at various length scales.

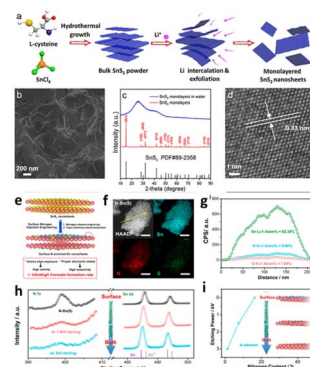
**2.3.1 Heteroatom doping.** Heteroatom doping can also be used to improve the electronic structure of electrocatalytic materials and tune  $CO_2$  adsorption.<sup>225</sup> This process changes the material's electronic structure, altering the interaction strength between reactants and active sites and influencing electronic transport near active sites, which improves catalytic activity.<sup>226</sup> He *et al.*<sup>227</sup> designed and developed a hybrid bimetallic composite catalyst of Ag nanowire and defective  $SnS_2$  nanosheets for  $CO_2$  reduction, as shown in Fig. 13a–c. Moreover, it was found that free electrons present in Ag nanowires enhance the electron mobility in  $SnS_2$  nanosheets, which improves the carrier density of Ag- $SnS_2$  hybrid nanosheets. Thus, the incorporation of Ag in defective  $SnS_2$  catalyst exhibited a maximum faradaic efficiency of 83.8% ( $FE_{HCOOH}$  of 65.5%) for producing carbonaceous products. Zeng *et al.*<sup>228</sup> developed a scheme of element-doping engineering for synthesized ultrathin  $SnS_2$  nanosheets with Ni atoms (Fig. 13d–f). These  $SnS_2$  thin nanosheets effectively reduced  $CO_2$  to formate with a greater current density and faradaic efficiency (FE) than pure  $SnS_2$  nanosheets. A mechanistic analysis found that Ni doping caused a defect level and decreased the work function of  $SnS_2$  nanosheets, resulting in increased  $CO_2$  activation and hence better  $CO_2$  electro-reduction performance. Likewise, in the  $ECO_2R$  application, Sargent *et al.*<sup>229</sup> fabricated Sulfur modulated tin ( $Sn(S)$ ) deposited on Au needles ( $Sn(S)/Au$ ) catalyst by a simple  $SnS_x$  atomic layer deposition (ALD) approach. The composite catalyst  $Sn(S)/Au$  observed a higher oxidation state than Sn nanoparticles and achieved a current density of 55  $mA\ cm^{-2}$  with a  $FE_{HCOOH}$  of 93% for  $CO_2$  electro-reduction. Fig. 13g–j shows that a small amount of S-doping (0–25%) into Sn could effectively reduce the Gibbs free energy ( $\Delta G$ ); in contrast, a more



**Fig. 13** (a) TEM image (b) HRTEM image and (c) XRD analysis of Ag-SnS<sub>2</sub> hybrid nanosheets (reprinted with permission from ref. 227. Copyright 2019, John Wiley & Sons, Inc); (d) TEM image (e) HRTEM image (f) XRD analysis of 5% Ni-SnS<sub>2</sub> nanosheets. (Reprinted with permission from ref. 228. Copyright 2019, John Wiley & Sons, Inc); computational investigation of (Sn(S)/Au) system (g) optimized surface slab structures of pure Sn, S-modulated Sn, and SnS. (h) Gibbs free energies of formation ( $\Delta G_{\text{formation}}$ ) for HCOO\* (yellow), COOH\* (gray), and H\* (blue) intermediates, which are the rate-limiting intermediates along the reaction pathway to produce formate, carbon monoxide, and hydrogen gas, respectively. (i) Volume slice of the charge densities through the middle of the oxygen atom of a bound HCOO\* intermediate. (j) Atomic accessible surface area of the metal slab normalized to the number of tin atoms as a function of sulfur content (reprinted with permission from ref. 229. Copyright 2017, Elsevier).

significant amount (25–50%) of S-doping into Sn can effectively increase the  $\Delta G$  (Fig. 13i). The DFT simulations showed that the formation of HCOOH compared to CO was favored by Sn nanoparticles, both with and without sulfur doping.

**2.3.2 Substrate coupling.** As described in Section 2.1.1, coupling the electrocatalyst layer with a conductive support with controlled mesoscale morphology is particularly effective: recently, unprecedented selectivity for formate production (FE of 92.6%) was achieved at a moderate overpotential of  $-0.9$  V *vs.* RHE using modified hollow nanotubes composed of SnS nanosheets with amino-functionalized carbon layers (SnS/aminated-C). The DFT theoretical calculation reveals high activity for formate production due to the synergistic effect of SnS and aminated-C, which enhances the electron transfer rate and higher the adsorption energies of OCHO\* and CO<sub>2</sub>\* intermediates. They reported a density of states (DOS) calculation. According to the analysis, after adsorbing OCHO\* on the SnS/aminated-C surface, it exhibits the highest peak of total DOS, which is close to the Fermi level than SnS, thus leading to a higher binding strength between SnS/aminated-C to OCHO\*.<sup>230</sup> Zhang and co-workers synthesized SnS<sub>2</sub> nanosheets well dispersed on reduced graphene oxide (SnS<sub>2</sub>/rGO) composite by a one-pot hydrothermal method and employed as a heterogeneous catalyst for ECO<sub>2</sub> R. The catalyst exhibited high formate selectivity with a faradaic efficiency of 84.5% at  $-0.68$  V (*vs.* RHE). They found that rGO, along with SnS<sub>2</sub>, stabilizes the intermediate (CO<sub>2</sub><sup>•-</sup>) during the reduction process and improves the catalyst's stability.<sup>231</sup>



**Fig. 14** Characterizations of SnS<sub>2</sub> monolayers. (a) Process used to synthesize; (b) SEM image; (c) XRD patterns of SnS<sub>2</sub> monolayers in the forms of powder and water dispersion; (d) HRTEM image; (reprinted with permission from ref. 232. Copyright 2018, Elsevier). (e) Illustration of synthesis from SnS<sub>2</sub> to N-Sn(S) nanosheets. (f) EDS mapping and (g) line scan of N-Sn(S) nanosheets. The scale bar is 30 nm. (h) *In situ* soft X-ray photoemission spectroscopy characterization of N, Sn elements in N-Sn(S). (i) The nitrogen content of different depth in N-Sn(S) nanosheets. (Reprinted with permission from ref. 233. Copyright 2020, American Chemical Society).

**2.3.3 Morphology and structure modulation.** Liu and co-workers synthesized SnS<sub>2</sub> monolayers (thickness of  $0.58 \pm 0.04$  nm) using a simple Li-intercalation/exfoliation method (Fig. 14a). In the case of SnS<sub>2</sub> monolayers, an interplanar spacing of 0.33 nm, corresponding to the (1 0 0) plane of SnS<sub>2</sub> is observed through HRTEM images (Fig. 14b–d). This electrocatalyst presented more than 90% FE for formate production with stability up to 80 h. Later, the theoretical analysis demonstrated that the thin atomic layers faster the crucial first step (CO<sub>2</sub><sup>•-</sup> radical formation) in producing HCOO\* intermediates, followed by proton–electron transfer processes resulting in formate production.<sup>232</sup> Similarly, Cheng *et al.*<sup>233</sup> enhanced the number of active sites, morphology and modified electronic structures of SnS<sub>2</sub> by surface nitrogen injection engineering (Fig. 14e). The derived surface nitrogen-enriched Sn(S) nanosheets, as shown in Fig. 14f–i provided better faradaic efficiency for formate production than SnS<sub>2</sub>-derived Sn nanosheets. DFT simulation confirmed that the better catalytic performance is due to the Sn site valence modulation. Their findings showed that the surface nitrogen-injection engineering techniques enhanced the ECO<sub>2</sub>R activity for other metal sulfides, such as CuS and In<sub>2</sub>S<sub>3</sub>.

**2.3.4 Polymorph engineering.** Polymorph engineering of SnS<sub>2</sub> is a practical approach to inhibit HER kinetics from achieving high ECO<sub>2</sub>R performance and selectivity. To suppress the high HER activity of the metallic phase of 1H-SnS<sub>2</sub>, Xu *et al.*<sup>234</sup> used a facile hydrogen-assisted low-temperature calcination technique to produce the meta-stable phase of the SnS<sub>2</sub> (1H-SnS<sub>2</sub>) catalyst. They compared the ECO<sub>2</sub>R activity between the stable semiconductor phase of SnS<sub>2</sub> (1T-SnS<sub>2</sub>) and the meta-stable semimetal phase (1H-SnS<sub>2</sub>). The novel nanosheets semimetal 1H-SnS<sub>2</sub> have an outstanding performance with a FE<sub>CO</sub> of more than 98% at  $-0.8$  V<sub>RHE</sub> (partial  $j_{\text{CO}}$  of 10.9 mA

## Review

$\text{cm}^{-2}$ ). Theoretical studies revealed that the more robust electron exchange between  $^*\text{COOH}$  intermediate and 1H-SnS<sub>2</sub> surface promotes CO formation.

## 2.4 Bismuth (Bi)-based sulfide

Bismuth sulfide (mineral bismuthinite) is a non-toxic and crystalline n-type V–VI group semiconductor material with a lamellar structure connected by weak Bi–S bonds.<sup>235</sup> It has a band gap energy value of 1.3 eV,<sup>236</sup> which is moderate but relatively higher than other sulfides in the similar group of metal chalcogenides of the type A<sub>2</sub>V<sub>3</sub><sup>VI</sup> (A = Sb, Bi, As; B = S, Se, Te).<sup>237</sup> With such extraordinary properties, Bismuth sulfide is widely used in different applications such as solar cells,<sup>238</sup> sodium-ion batteries,<sup>239</sup> supercapacitors,<sup>240</sup> thermoelectric materials,<sup>241</sup> photoanode,<sup>242</sup> and so on.<sup>243</sup> This section will focus on bismuth sulfide-based electrocatalysts in their defect sites, interfacial phenomena, and morphological structure for CO<sub>2</sub> reduction application.

**2.4.1 Substrate coupling.** As identified in Section 2.1.1, coupling with conductive supports, generally carbon-based, improves both the electrochemical surface area and the conductivity of the catalytic framework: Liu *et al.*<sup>244</sup> prepared composites electrocatalyst S-doped Bi<sub>2</sub>O<sub>3</sub> nanosheets (NSs) coupled with carbon nanotubes (S-Bi<sub>2</sub>O<sub>3</sub>-CNT) for improved catalytic activity towards CO<sub>2</sub> to HCOOH production (Fig. 15a–g). According to Fig. 15h and i, the HCOOH pathway is more energy-favorable than the CO pathway because the Gibbs free energy (*G*) for the production of  $^*\text{COOH}$  (the intermediate for the CO pathway) is higher than that of  $^*\text{HCOO}$  (the intermediate for the HCOOH pathway). DFT calculations indicate that less electronegative S doping was attributed to higher charge density distribution and electronic delocalization of Bi (Fig. 15j and k), which increased the adsorption of  $^*\text{CO}_2$  and  $^*\text{HCOO}$  intermediates while preventing  $^*\text{H}$  adsorption. As a result, S-Bi<sub>2</sub>O<sub>3</sub> enhances formate production while suppressing HER.

**2.4.2 Defect engineering.** Bismuth sulfide is another potential metal sulfide-based electrocatalyst, which can be used as a suitable catalyst for ECO<sub>2</sub>R by constructing lattice defects: Zhang *et al.*<sup>245</sup> showed that lattice defects in Bi-based catalysts strongly influenced formate production in ECO<sub>2</sub>R. They observed that sulfur-derived Bi (SD-Bi) was exposed to more lattice defects owing to the release of lattice sulfur during the catalysis. Sulfur-derived Bi with structural lattice defects achieved high faradaic efficiency (maximum 84.0% at a potential of  $-0.75$  V with a stability of 24 h), which has the best performance compared to the high crystalline SD-Bi catalysts under similar conditions. The authors also reported that though the selectivity of lattice defect-rich Bi derived from Bi<sub>2</sub>S<sub>3</sub> was high, the catalytic current density needs to be enhanced.

In another work, Yang *et al.*<sup>246</sup> studied the role of defects and specific interfacial phenomena between bismuth oxide and bismuth sulfide (Bi<sub>2</sub>S<sub>3</sub>–Bi<sub>2</sub>O<sub>3</sub>). They used the partial precipitation conversion method to create many defects, including oxygen vacancies and lattice distortions. The hybrid catalysts Bi<sub>2</sub>S<sub>3</sub>–Bi<sub>2</sub>O<sub>3</sub>/rGO achieved unprecedented selectivity of over 90% for formate production with a stability of more than 24 h.

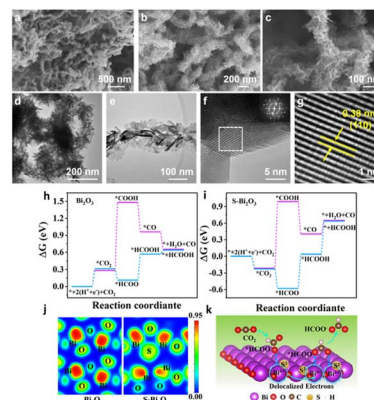


Fig. 15 (a–c) Field emission scanning electron microscopy (FESEM) images of S<sub>2</sub>-Bi<sub>2</sub>O<sub>3</sub>-CNT with different magnifications. (d–g) TEM images of S<sub>2</sub>-Bi<sub>2</sub>O<sub>3</sub>-CNT with different magnifications. Gibbs free energy diagrams for ECO<sub>2</sub>R to CO and HCOOH on (h) Bi<sub>2</sub>O<sub>3</sub> (110) and (i) S-Bi<sub>2</sub>O<sub>3</sub> (110) surface. (j) Charge density distribution of Bi<sub>2</sub>O<sub>3</sub> and S-Bi<sub>2</sub>O<sub>3</sub>. (k) Schematic illustration for the role of S in promoting the reduction of CO<sub>2</sub> to formate (reprinted with permission from ref. 244. Copyright 2021, American Chemical Society).

Mechanistic studies also reveal that the Bi<sub>2</sub>S<sub>3</sub>–Bi<sub>2</sub>O<sub>3</sub> interface provides rich-defect sites as well as oxygen vacancies, thus offering more active sites that lowered the binding energy of the HCOO\* intermediates, and the HCOOH product selectivity improved.

**2.4.3 Interfacial engineering.** A metal–semiconductor junction can modulate both the band positions of the semiconductor and the d-band center of the surface-active atoms. It thus helps to lower the activation barrier of CO<sub>2</sub> and suppress the competitive HER and hence improve the faradaic efficiency. In this regard, Shao *et al.*<sup>247</sup> successfully prepared a series of Bi–Bi<sub>2</sub>S<sub>3</sub> by a facile one-pot solvothermal synthesis method. The High-resolution TEM (HRTEM) analysis of Bi–Bi<sub>2</sub>S<sub>3</sub> revealed the visible lattice fringes of 0.36 nm and 0.3 nm, confirming to Bi<sub>2</sub>S<sub>3</sub> (221) and Bi (012) planes, respectively. Dark-field TEM images with EDS elemental mappings of Bi–Bi<sub>2</sub>S<sub>3</sub> nanorod unveil those Bi and S elements uniformly dispersed throughout the structure. Formate was the highly selective main product at high faradaic efficiency of 85%, accredited to the synergistic coupling effect of co-catalyst structure. The maximum current density reached a maximum of 17 mA cm<sup>-2</sup> for Bi–Bi<sub>2</sub>S<sub>3</sub>, which is comparably better than the current density (12.9 mA cm<sup>-2</sup>) observed for Bi<sub>2</sub>S<sub>3</sub> catalysts. They also concluded that the synergistic effect between Bi<sub>2</sub>S<sub>3</sub> and Bi<sup>0</sup> contributes to better product selectivity in high potentials.

**2.4.4 Morphology and structure modulation.** Several researchers found that carbonate ( $^*\text{CO}_3\text{H}$ ) intermediate adsorbed on the catalyst surface, which further reduced to  $^*\text{COOH}$  and  $^*\text{OOCH}$  intermediates, might also be enhanced for formate production.<sup>248</sup> In this regard, Wang *et al.*<sup>249</sup> prepared sulfur-modulated bismuth subcarbonate nanosheets using a facile hydrothermal method. They reported that sulfur incorporation significantly enhanced the local electron density around the Bi active sites and promoted proton-coupled electron transfer. The two-dimensional sulfur-doped bismuth subcarbonate (S-BiOC)

nanosheet contributed excellent  $\text{CO}_2$  reduction with more than 90%  $\text{FE}_{\text{HCOOH}}$ , a broad negative potential range, and high partial current density.

Generally, like monolayers, nanosheets with highly active sites should be as thin as possible. But Wang *et al.*<sup>250</sup> demonstrated that it is not always 'the Thinner the Better.' They developed a microkinetic model that exhibited by considering the stabilization energy evolved by the spin-orbit coupling (SOC) effect; the Bi bilayer was found to have the most excellent catalytic activity of all the Bi nanosheets.

## 2.5 Molybdenum (Mo)-based sulfide

Molybdenum, a VIB group material, is a promising candidate for electrocatalytic applications. Among all the molybdenum (Mo)-based materials, molybdenum disulfide ( $\text{MoS}_2$ ) exhibited better HER activity, attracting huge research attention in the past few years.<sup>251</sup> Before the twenty-first century, Molybdenum disulfide ( $\text{MoS}_2$ ) was discarded as a prospective candidate as bulk  $\text{MoS}_2$  was found to be inactive for electrochemical applications. In 2006, theoretical DFT studies discovered that the edge-exposed  $\text{MoS}_2$  sites showed excellent catalytic activity,<sup>252</sup> further validated by Jaramillo *et al.*<sup>253</sup> using an experimental approach. The electrochemical assessment results exhibited that the catalytic activity was linearly allied with the number of exposed sites on the  $\text{MoS}_2$  catalyst.<sup>254</sup> Molybdenum disulfide ( $\text{MoS}_2$ ), as a two-dimensional (2-D) layered structure, offers high surface area, large electrical conductivity, and is rich in active sites. As van der Waal forces assembled these two-dimensional layers,  $\text{MoS}_2$  can be considered a single sheet composed of multiple-layer nanosheets with edges having exposed active sites because of metallic properties and high d-electron density.<sup>255</sup>

The weak van der Waals interaction holds the stacked parallel layers of bulk  $\text{MoS}_2$ , just like graphite.<sup>251</sup> In 2014, Asadi *et al.*<sup>256</sup> first reported layer-stacked bulk  $\text{MoS}_2$  with Mo-terminated edge catalyst towards the  $\text{ECO}_2\text{R}$  process. They observed that inexpensive and adaptable bulk- $\text{MoS}_2$  achieved high catalytic performance ( $\text{FE}_{\text{CO}}$  of more than 95% and a higher current density of  $65 \text{ mA cm}^{-2}$  at  $-0.764 \text{ V vs. RHE}$ ) for  $\text{CO}_2$  reduction than costly noble metals such as Ag and Au. The higher current density in  $\text{CO}_2$  reduction occurred mainly due to higher d-electron density in the Mo-terminated edges. This research suggested that TMCs can replace expensive noble metal catalysts (Ag, Au) for  $\text{CO}_2$  reduction accompanied by product conversion and selectivity.

**2.5.1 Substrate coupling.** The edge site modification of the  $\text{MoS}_2$  with carbonaceous support such as graphene,<sup>257,258</sup> CNTs,<sup>259,260</sup> carbon fibers/clothes,<sup>261</sup> and porous amorphous carbon<sup>262</sup> are necessary for  $\text{ECO}_2\text{R}$  and have been shown to enhance the catalytic efficiency and catalyst regeneration. For example, Li *et al.*<sup>263</sup> developed reduced graphene oxide supported polyethyleneimine-modified amorphous molybdenum sulfide, a low-cost catalyst for  $\text{ECO}_2\text{R}$  to CO in an aqueous medium. The synergistic interaction between the  $\text{MoS}_x$  and polyethyleneimine (PEI) catalyst reduced the activation energy for the conversion of the intermediates and enabled the  $\text{CO}_2$ -

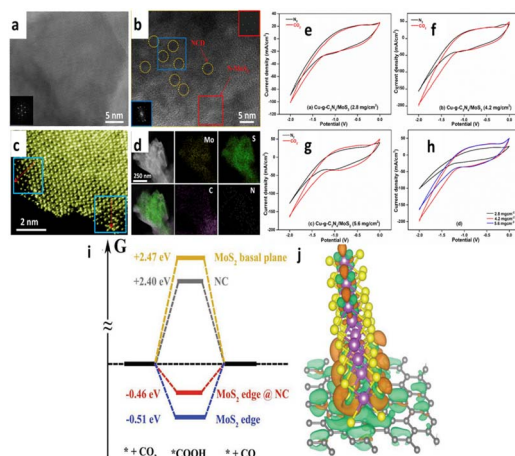


Fig. 16 HRTEM images of (a) E- $\text{MoS}_2$ . (b) N- $\text{MoS}_2$ @NCDs-180, the blue frame represents NCD and the red frame represents N- $\text{MoS}_2$ . (c) Higher magnification HAADF image of N- $\text{MoS}_2$ @NCDs-180 shows clearly distinct atomic configuration. (d) TEM image and corresponding elemental mappings of the N- $\text{MoS}_2$ @C-180 nanosheets (reprinted with permission from ref. 264. Copyright 2019, Elsevier). CV of Cu-g- $\text{C}_3\text{N}_4$ / $\text{MoS}_2$  composite material in  $\text{N}_2$  and  $\text{CO}_2$  saturated  $\text{KHCO}_3$  solution with different catalytic loading such as (e)  $2.8 \text{ mg cm}^{-2}$ , (f)  $4.2 \text{ mg cm}^{-2}$ , and (g)  $5.6 \text{ mg cm}^{-2}$ ; (h) comparison of CV of the Cu-g- $\text{C}_3\text{N}_4$ / $\text{MoS}_2$  composite with different catalytic loading in  $\text{CO}_2$  saturated  $\text{KHCO}_3$  solution (0.5 M) (reprinted with permission from ref. 265. Copyright 2022, Elsevier). (i) The DFT calculations for demonstrating free energy profiles for  $\text{ECO}_2\text{R}$  catalyzed by different models at the equilibrium potential of  $-0.11 \text{ V}$ . (j) The illustration of electron density changes in the NCMSH model (reprinted with permission from ref. 266. Copyright 2019, John Wiley & Sons, Inc).

reduction reaction at low potentials. They further reported that rGO as a substrate material increased electrical conductivity and catalytic stability.

Zhu *et al.*<sup>264</sup> prepared Nitrogen-doped  $\text{MoS}_2$  (N- $\text{MoS}_2$ ) nanosheets and nitrogen-doped carbon nanodots (NCDs) composite for  $\text{ECO}_2\text{R}$  catalysts by a simple solvothermal method in the presence of exfoliated- $\text{MoS}_2$  and DMF as a solvent. As depicted in Fig. 16a–d, the HRTEM images explored a clear lattice fringe above the surface of N- $\text{MoS}_2$  nanosheets due to the uniform distribution of NCDs (diameter of 6 nm). The composite catalyst N- $\text{MoS}_2$ @NCDs-180 with the high N content (8.35 at%) achieved  $\text{FE}_{\text{CO}}$  over 90% with a low onset potential. Energy calculations exposed that the N-doping procedure enhanced the electron density on the edge sites of  $\text{MoS}_2$ , which significantly decreases the energy barrier of the  $\text{COOH}^*$  intermediates, consequently promoting CO formation. Hussain *et al.*<sup>265</sup> found that Cu-g- $\text{C}_3\text{N}_4$ / $\text{MoS}_2$  hybrid material exhibited a much greater faradaic efficiency (19.7% and 4.8% for methanol and ethanol, respectively) compared to g- $\text{C}_3\text{N}_4$ ,  $\text{MoS}_2$ , Cu-g- $\text{C}_3\text{N}_4$ , and Cu- $\text{MoS}_2$  in terms of current density and reduction potential (Fig. 16e–h). This increase in faradaic efficiency was attributed to high electrochemically active surface area (ECSA) and the synergistic effect between their components. The chronoamperometric study of the Cu-g- $\text{C}_3\text{N}_4$ / $\text{MoS}_2$  hybrid material presented its long-term stability, without any decay in the current density, for up to 30 h. In another study, Li and the group prepared a hierarchical

hollow composite electrocatalyst of N-doped carbon (NC) and edge-exposed 2H MoS<sub>2</sub> (NCMSH). Theoretical analysis as shown in Fig. 16i revealed that the intermediates energy profiles for electrochemical CO<sub>2</sub> reduction activity for different models and the MoS<sub>2</sub> edge@NC catalyst (with an overpotential of 0.46 V) was the most effective among all the tested models. They also predicted that Mo sites stabilizes after taking electrons from the NC, which enhances more active edges exposed Mo sites and accelerates the electrocatalytic activity (Fig. 16j).<sup>266</sup>

**2.5.2 Heteroatom doping.** The effect of metal centers can synergistically affect the electrochemical performance of MoS<sub>2</sub>. For example, Shi *et al.*<sup>267</sup> developed Cu nanoparticles interspersed with MoS<sub>2</sub> nanoflowers for selective conversion of CH<sub>4</sub> in an aqueous electrolyte. Compared to MoS<sub>2</sub> nanosheet electrode (−2.4% at −1.4 V<sub>SCE</sub> and 4 mA cm<sup>−2</sup> at −1.7 V<sub>SCE</sub>, respectively), the designed Cu/MoS<sub>2</sub> composite achieved a better faradaic efficiency (17.08% at −1.4 V vs. saturated calomel electrode) and electron conductivity (−17 mA cm<sup>−2</sup> at −1.7 V<sub>SCE</sub>) for CH<sub>4</sub> formation. The use of Cu nanoparticles as a doping material has achieved unprecedented results for the reduction of CO<sub>2</sub> due to their enhanced electronic conductivity, higher specific surface area (51.6 m<sup>2</sup> g<sup>−1</sup>), and synergetic effect between Cu NPs and MoS<sub>2</sub>. In a similar work, Abbasi *et al.*<sup>268</sup> synthesized niobium-doped on vertically oriented MoS<sub>2</sub> with 20 nm thickness *via* the chemical vapor decomposition (CVD) method. Their findings revealed that a lesser amount of Nb atoms on Mo edges increased the TOF value for CO production and modified the binding energies of the reaction intermediates to the MoS<sub>2</sub> edge.

**2.5.3 Interfacial engineering.** Recently, Hussain *et al.*<sup>269</sup> employed a facile solution chemistry approach to synthesize non-noble metal-based Cu<sub>2</sub>O nanoparticles decorated MoS<sub>2</sub>-(Cu<sub>2</sub>O-MoS<sub>2</sub>) nanosheets using an environmentally benign reducing agent Glucose. They observed that the composite material (Cu<sub>2</sub>O-MoS<sub>2</sub>) exhibited exceptional ECO<sub>2</sub>R activity, with a current density of 113 mA cm<sup>−2</sup>, almost two times that of bare Cu<sub>2</sub>O (61 mA cm<sup>−2</sup>) and eightfold that of MoS<sub>2</sub> nanosheet (21.3 mA cm<sup>−2</sup>). The authors attribute this improvement in catalytic activity because of the synergistic effect between the Cu<sub>2</sub>O-MoS<sub>2</sub> composite catalyst. The faradaic efficiency of the composite catalyst depends on the applied potential, reaching a maximum of 12.3% for methanol and 7.9% for ethanol at −1.3 V<sub>RHE</sub> and −1.1 V<sub>RHE</sub>, respectively. Electrochemical impedance spectroscopy (EIS) study exhibited that the composite catalyst with a catalytic loading of 4.8 mg cm<sup>−2</sup> presented an excellent electrocatalytic activity due to increase in charge transfer and decrease in ohmic resistance. The chronoamperometric studies examined the stability of Cu<sub>2</sub>O-MoS<sub>2</sub> composite material in CO<sub>2</sub> reduction.

**2.5.4 Polymorph engineering.** Polymorph engineering of MoS<sub>2</sub> is an effective approach to tune its electronic conductivity: a study by Lv *et al.*<sup>270</sup> shows that hydrophobic exfoliated MoS<sub>2</sub> (H-E-MoS<sub>2</sub>) nanosheets modified fluorosilane (FAS) act as an active CO<sub>2</sub> electroreduction catalyst under aqueous medium (Fig. 17a–d). The HRTEM images (Fig. 17e and f) and fast Fourier transform (inset) revealed that the E-MoS<sub>2</sub> layers were composed of two clearly distinct structural domains consisting

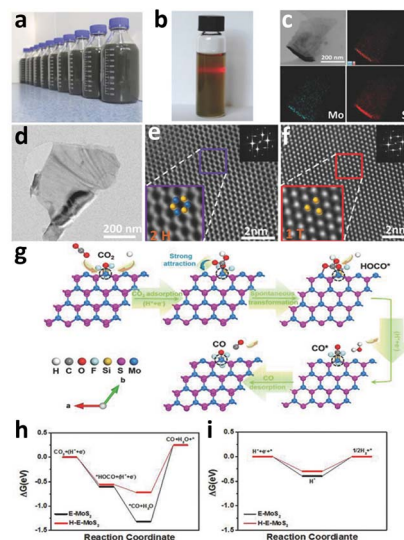


Fig. 17 (a) Digital photo of the exfoliated MoS<sub>2</sub> (E-MoS<sub>2</sub>) nanosheets in NVP with a concentration of 3 mg mL<sup>−1</sup> after ball milling. (b) Tyndall effect of the diluted E-MoS<sub>2</sub> dispersion. (c) TEM image of E-MoS<sub>2</sub> nanosheet and corresponding EDX maps, showing clearly the homogeneous distribution of Mo and S. (d) HRTEM image of an E-MoS<sub>2</sub> nanosheet. (e and f) Higher magnification HRTEM images of an E-MoS<sub>2</sub> nanosheet, showing atomic-resolution structural information, and their corresponding fast Fourier transforms (FFTs). Insets show the 2H and 1T phases in (e and f), respectively. (g) Schematic representation of CO formation mechanism on the H-E-MoS<sub>2</sub> monolayers. The atoms in the dashed circle are the catalytic sites (Mo atoms). Calculated free energy diagrams for (h) CO<sub>2</sub> electroreduction to CO and (i) the HER (reprinted with permission from ref. 270. Copyright 2018, John Wiley & Sons, Inc).

of a 1T (trigonal) phase and a 2H (hexagonal) phase, and the magnified images of selected regions further confirmed the coexistence of both 1T and 2H phases and is regarded to be a key to enhanced performance and stable selectivity. According to Fig. 17h and i, DFT results suggested that the FAS anchored on H-E-MoS<sub>2</sub> modified the electrical conductivity of the MoS<sub>2</sub> layer and lowered the energy barrier of the rate-determining CO-desorption step while increasing the energy barrier of H desorption. The reaction mechanism is also described in detail, as shown in Fig. 17g. Briefly, the single Mo atom of the H-E-MoS<sub>2</sub> adsorbs CO<sub>2</sub> and is combined with a proton–electron pair (H<sup>+</sup> + e<sup>−</sup>) to generate HOCO\* intermediate. The HOCO\* intermediate further evolved into a more stable structure in which HOCO\* connected with two nearby Mo atoms. Subsequently, the HOCO\* intermediate reacts with H<sup>+</sup> and e<sup>−</sup> to create the product. Therefore, in 2019, Chen *et al.*<sup>271</sup> employed DFT calculations to study ECO<sub>2</sub>R on molybdenum sulfide monolayer with 2S vacancy in the 2H phase MoS<sub>2</sub> (DV-MoS<sub>2</sub>) basal plane. Detailed electronic studies showed that steric hindrance in the DV-MoS<sub>2</sub> basal plane enhances CO-CH<sub>4</sub> conversion with high catalytic activities and product selectivity. In 2019, Kang *et al.*<sup>272</sup> used the modified CHE model to theoretically predicts possible electrochemical pathways for ECO<sub>2</sub>R on V<sub>5</sub>-MoS<sub>2</sub>. The group demonstrated that the condensation of HCHO molecules is essential for forming C–C coupling at V<sub>5</sub>. The CHE model

predicts that routes to multiple CN species for  $N < 4$  can open at 0.40 V, whereas C4 product formation is unfavorable at such low potentials. These findings are consistent with the recent experiment, indicating that the  $V_S$  of  $\text{MoS}_2$  is an essential active site for  $\text{ECO}_2\text{R}$ . They also reported that by implementing cascade catalysts and doping,  $\text{ECO}_2\text{R}$  selectivity improves against HER.

**2.5.5 Morphology and structure modulation.** As reported, ordinary binary TMDs typically showed low electrical conductivity, less active sites, and low intrinsic activity, which limited their electrochemical activity. Notably, the latest research found that ternary TMDs alloy monolayers possessed an ultra-high ratio of surface exposed atoms that potentially serve as the relatively single active sites.<sup>273–275</sup> Therefore, to check the faradaic efficiency, Xie and co-workers fabricated ternary TMDs alloy monolayers ( $\text{MoSeS}$ ) for  $\text{ECO}_2\text{R}$ . Their catalytic system resulted in  $\text{FE}_{\text{CO}}$  of  $\sim 45\%$ , which was remarkably more than those of  $\text{MoS}_2$  ( $\sim 16\%$ ) and  $\text{MoSe}_2$  ( $\sim 30\%$ ) monolayers at  $-1.15 V_{\text{RHE}}$ . They exhibited a current density of  $43 \text{ mA cm}^{-2}$  against  $-1.15 V_{\text{RHE}}$  which was 1.3 times that in  $\text{MoS}_2$  and  $\text{MoSe}_2$  monolayers. The monolayers ( $\text{MoSeS}$ ) increase  $\text{CO}_2$  adsorption and  $\text{CO}$  desorption rate with a low work function. The catalyst was found to be excellent for syngas formation as the only product.<sup>276</sup> In another study, Chan *et al.*<sup>277</sup> performed pioneering work by applying the QUANTUM ESPRESSO code and the BEEF-vdW exchange-correlation functional in investigating the electrocatalytic effect of S and Se in the reductive decomposition of  $\text{CO}_2$  in aqueous media. The calculations indicate that combining S or Se atoms at the edge sites of TMDs monolayers promoted the binding of CHO and COOH intermediates rather than CO. They also reported that CO could be further reduced to hydrocarbons and alcohols by the S edges of Ni-doped  $\text{MoS}_2$  and the Mo edges of  $\text{MoSe}_2$ . However, S edges in undoped and Ni-doped  $\text{MoS}_2$  were found to suppress the HER and accelerate the  $\text{ECO}_2\text{R}$  compared to Mo edge sites. This research demonstrated that edge site tuning of TMDs should be tailored for improved  $\text{CO}_2$  reduction.

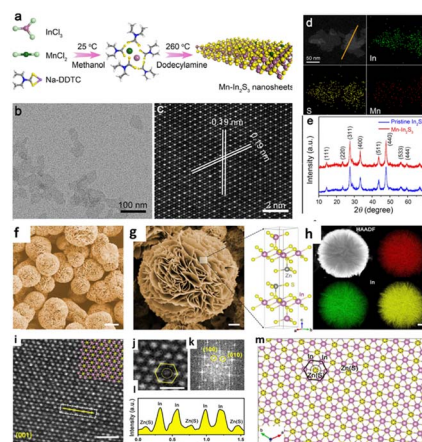
## 2.6 Indium (In)-based sulfide

$\text{In}_2\text{S}_3$ , a common III–VI main-group chalcogenide, exists in three crystallographic forms: a defective cubic structure  $\alpha\text{-In}_2\text{S}_3$ , a defect spinel structure  $\beta\text{-In}_2\text{S}_3$ , and a higher-temperature-layered structure  $\gamma\text{-In}_2\text{S}_3$ .<sup>278</sup> Besides, several  $\text{In}_2\text{S}_3$  nanostructures, including nanoflakes,<sup>279</sup> nanosheets,<sup>280</sup> and flower-like microspheres,<sup>281</sup> were reported for electrochemical applications.

**2.6.1 Heteroatom doping.** Metal doping have also been widely used to modify electrocatalysts to bring about charge redistribution on the surface to adjust the  $\text{ECO}_2\text{R}$  activation.<sup>225,226</sup> Yuan *et al.*<sup>282</sup> modified  $\text{In}_2\text{S}_3$  nanosheets doped with *in situ* formed metallic In atoms ( $\text{In-In}_2\text{S}_3$ ) for the  $\text{ECO}_2\text{R}$  process. The hybrid electrocatalyst achieved a higher current density of  $70.3 \text{ mA cm}^{-2}$  at  $-1.1 \text{ V vs. RHE}$  with a faradaic efficiency of 90% at  $-1.0 V_{\text{RHE}}$  (76% for  $\text{HCOOH}$  generation and 14% for  $\text{CO}$  generation). Similarly, Zhang *et al.*<sup>283</sup> synthesized thin  $\text{Mn-In}_2\text{S}_3$  nanosheets and observed high faradaic efficiency

(90% at  $-0.9 V_{\text{RHE}}$  with a current density of  $20.1 \text{ mA cm}^{-2}$ ) for formate production (Fig. 18a–e). The mechanistic study demonstrated that Mn doping facilitated harmonic overlaps between the p orbitals of O atoms of  $\text{CO}_2$  and the d orbitals of Mn atoms near the conduction band edge of the  $\text{Mn-In}_2\text{S}_3$  slab. The unique structure lowered the energy barrier for initial  $\text{CO}_2$  adsorption to form  $\text{HCOO}^*$  intermediates; thus, they achieved effective  $\text{CO}_2$ -to- $\text{HCOOH}$  conversion. In another work, Chi *et al.*<sup>284</sup> prepared Zn-modulated indium sulfide ( $\text{In}_2\text{S}_3$ ), and the resultant catalysts  $\text{ZnIn}_2\text{S}_4$  exhibited long-term stability for  $\text{ECO}_2\text{R}$  (Fig. 18f–h). The synthesis procedure enabled the modification of its phase and structure without affecting the morphology of the catalyst (Fig. 18i–m). Experimental and theoretical studies demonstrated that incorporating Zn enhanced the covalency of In–S bonds and stabilized sulfur – a catalytic site activating  $\text{H}_2\text{O}$  to combine with  $\text{CO}_2$ , resulting in the formation of the  $\text{HCOO}^*$  intermediates. Thus,  $\text{ZnIn}_2\text{S}_4$  achieved unprecedented  $\text{CO}_2$  to formate production with stability up to 60 h.

**2.6.2 Morphology and structure modulation.** Feng *et al.*<sup>285</sup> studied the catalytic behavior of flower-like  $\text{In}_2\text{S}_3$  assembled by nanoflakes catalyst for  $\text{CO}_2$  conversion to  $\text{HCOOH}$  (Fig. 19a and b). The flower-like structure  $\text{In}_2\text{S}_3$  electrocatalyst achieved higher formate selectivity ( $\text{FE}_{\text{HCOOH}}$  of 86%) compared to bulk  $\text{In}_2\text{S}_3$  ( $\text{FE}_{\text{HCOOH}}$  of 63%) prepared *via* the hydrothermal method. The mechanistic studies explain that the complete route of  $\text{ECO}_2\text{R}$  to formate involves two-electron and two-proton transfer



**Fig. 18** (a) Scheme of the synthetic procedure of  $\text{Mn-In}_2\text{S}_3$  nanosheets. (b) TEM image of  $\text{Mn-In}_2\text{S}_3$  nanosheets. (c) HAADF-STEM image of an individual  $\text{Mn-In}_2\text{S}_3$  nanosheet. (d) HAADF-STEM and STEM-EDX elemental mapping images of the  $\text{Mn-In}_2\text{S}_3$  nanosheet. (e) XRD patterns of pristine  $\text{In}_2\text{S}_3$  and  $\text{Mn-In}_2\text{S}_3$  nanosheets. (Reprinted with permission from ref. 283. Copyright 2019, American Chemical Society); physical characterization of  $\text{ZnIn}_2\text{S}_4$ . (f and g) SEM images of the  $\text{ZnIn}_2\text{S}_4$  catalyst. The right panel in (g) shows the crystal structure of  $\text{ZnIn}_2\text{S}_4$ . Scale bars, 5  $\mu\text{m}$  (f) and 1  $\mu\text{m}$  (g). (h) STEM-EDX elemental mapping of  $\text{ZnIn}_2\text{S}_4$ , exhibiting a uniform spatial distribution of Zn (red), In (green), and S (yellow), respectively. Scale bar, 1  $\mu\text{m}$ . (i and j) Atomic-resolution Z-contrast images of  $\text{ZnIn}_2\text{S}_4$  along [001] zone axis. Scale bars, 1 nm (i) and 0.5 nm (j). (k) The corresponding FFT pattern of (i). (l) The line intensity profile acquired along the yellow arrow in (i). (m) Atomic model of  $\text{ZnIn}_2\text{S}_4$  along [001] zone axis. (Reprinted with permission from ref. 284. Copyright 2021, Nature Publishing Group).

processes *via* adsorbed  $\text{CO}_2$  ( $\text{CO}_2^*$ ) and  $\text{OCHO}^*$  intermediate. They employed DFT to calculate the adsorption energy of intermediates on the main exposed (311), (440) facets of flower-like  $\text{In}_2\text{S}_3$ , and (400) facets of bulk  $\text{In}_2\text{S}_3$ . The results depicted (440) facet shows the most negative adsorption energy on both  $\text{CO}_2^*$  and  $\text{OCHO}^*$ ; this indicates (440) facet is advantageous to the binding of  $\text{CO}_2$  and stabilizing  $\text{OCHO}^*$ , which are convenient for decreasing onset potential and enhancing selectivity of formate, respectively.

In a recent report, Ma and the groups developed sulfur-doped indium (S-In) catalysts for efficient  $\text{CO}_2$  reduction to formate (Fig. 19c and d). They fabricated a number of S-In catalysts with changing sulfur proportions by electro-reduction of sulfur-containing  $\text{In}_2\text{O}_3$  precursors *via* the hydrothermal method. The S-In catalyst with 4.9 mol% sulfur content showed an exceptional formate generation rate of  $1002 \mu\text{mol h}^{-1} \text{cm}^{-2}$  with more than 90% FE, 17 and 1.6 times higher than the In foil. Furthermore, the S-In catalysts possessed high formate FE (>85 percent) for  $\text{ECO}_2\text{R}$  in aqueous alkaline environments over a wide current density range ( $25\text{--}100 \text{ mA cm}^{-2}$ ). The production rate of formate in  $\text{C}_6\text{H}_5\text{CO}_3$  aqueous solution climbs to  $1449 \mu\text{mol h}^{-1} \text{cm}^{-2}$  with a current density of  $84 \text{ mA cm}^{-2}$  and FE of 93%. As shown in Fig. 19e, DFT calculation exhibited the

optimal adsorption configurations of reactants, intermediates, and products on indium and sulfur-doped indium surfaces. Theoretical studies also demonstrated that, for the  $\text{HCOOH}$  pathway, S-In catalysts minimize the Gibbs free energy for forming  $^*\text{COOH}$  intermediates from 0.29 eV to  $-0.16 \text{ eV}$  (Fig. 19f); and for the  $\text{CO}$  pathway, the Gibbs free energies for the formation of  $^*\text{COOH}$  intermediates are 1.49 and 0.82 eV on bare In and S-In surfaces, respectively (Fig. 19g). Based on the DFT results, they suggested that the surface  $\text{S}^{2-}$  species acts as an anchor to keep the  $\text{K}^+(\text{H}_2\text{O})_n$  cation near to indium surfaces in the double layer *via* Coulomb interactions (Fig. 19i). As a result, the presence of sulfur on the indium surface provides a substantial energy advantage to the  $\text{HCOOH}$  pathway (Fig. 19h). However, tailoring In with Se and Te can enhance the FE with a higher formate generation rate, similar to sulfur. More interestingly, the group also identified as the electronegativity of chalcogen atoms is reduced, their affinity to adsorb  $^*\text{H}$  species decreases, and the rate of formate generation also falls in the order  $\text{S-In} > \text{Se-In} > \text{Te-In}$ .<sup>286</sup>

## 2.7 Lead (Pb)-based sulfide

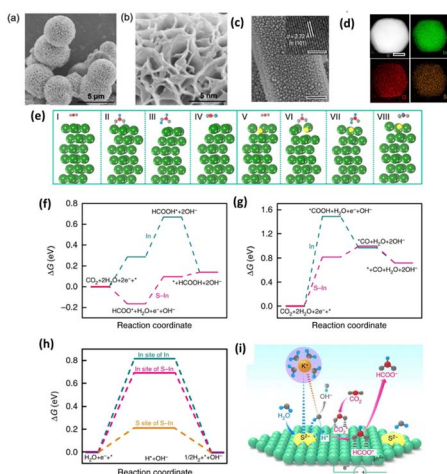
Similar to other metals, *i.e.*, Sn and In, metallic Pb electrodes in aqueous electrolytes are also beneficial for producing  $\text{HCOOH}$ . In 1985, Hori *et al.* first reported Pb metal electrode in an aqueous solution for  $\text{CO}_2$  to formate production.<sup>41</sup> Earlier studies reported that among Sulfide-derived (SD)-Pb, oxide-derived (OD)-Pb, and Pb cathodes, SD-Pb showed high catalytic activity for formate generation.<sup>287</sup> However, the application of PbS is still limited in the  $\text{ECO}_2\text{R}$  process.

**2.7.1 Morphology and structure modulation.** Recently, Pander *et al.*<sup>288</sup> emphasized the relation between catalyst morphology and  $\text{HCOOH}$  formation. They prepared S-derived Pb and O-derived Pb by reducing the PbS and  $\text{PbO}_x$  precursors. Compared to O-derived Pb (derived from  $\text{PbO}$ ), the wafer-structured S-derived Pb showed better stability and catalytic activity ( $\text{FE}_{\text{HCOOH}}$  of 88% and  $j_{\text{HCOO}^-,\text{geom}}$  of  $12 \text{ mA cm}^{-2}$  at  $-1.08 \text{ V}_{\text{RHE}}$ ) in 0.1 M  $\text{KHCO}_3$  electrolyte. This work showed that wafer-structured SD-Pb exhibited better  $\text{ECO}_2\text{R}$  performance.

In a different report, Zhang *et al.*<sup>289</sup> used a hot-injection colloidal approach to create well-defined PbS nanocrystals (NCs) with tuneable sizes ranging from 5 to 12 nm. They investigated that during electrochemical  $\text{CO}_2$  reduction, the PbS NCs undergo restructuring to Pb thin films, which achieved >90%  $\text{FE}_{\text{formate}}$  over a wide range of  $-1.0$  to  $-1.2 \text{ V vs. RHE}$  and a maximum mass activity of  $69.8 \text{ mA mgPb}^{-1}$ . With the aid of an *in situ* synchrotron radiation X-ray diffraction (SR-XRD) technique, the authors demonstrated that during the PbS-to-Pb structural transformation, initially  $\text{PbCO}_3$  is generated from the anion exchange in PbS between  $\text{CO}_2/\text{HCO}_3^-/\text{CO}_3^{2-}$  and  $\text{SCN}^-$  (generated by the anion-exchange), as well as  $\text{S}^{2-}$ . And then  $\text{PbCO}_3$  further reduced to Pb thin films.

## 2.8 Zinc (Zn)-based sulfide

Zinc sulfides are well-known semiconductor materials with appropriate large band gaps. With such distinct properties, zinc sulfide based materials have been employed in photocatalysis,



**Fig. 19** SEM images of flower-like  $\text{In}_2\text{S}_3$ , (a) low-magnification and (b) high-magnification (reprinted with permission from ref. 285. Copyright 2019, John Wiley & Sons, Inc); characterizations of morphologies and chemical states for S-In catalysts. (c) SEM image and HRTEM image (insert) of  $\text{S}_2\text{-In}$  catalyst. (d) STEM image of  $\text{S}_2\text{-In}$  catalyst and the corresponding EDS elemental mapping. DFT calculation and reaction scheme (e) optimized configurations of (I)  $\text{CO}_2$ , (II)  $\text{HCOO}^*$ , (III)  $\text{HCOOH}^*$ , (IV)  $\text{HCOOH}$  on (101) facet of pure indium (In) and (V)  $\text{CO}_2$ , (VI)  $\text{HCOO}^*$ , (VII)  $\text{HCOOH}^*$ , (VIII)  $\text{HCOOH}$  on (101) facet sulfur-doped indium (S-In). (f) Gibbs free energy diagrams for  $\text{ECO}_2\text{R}$  to  $\text{HCOOH}$  on In (101) and S-In (101) surfaces. (g) Gibbs free energy diagrams for  $\text{ECO}_2\text{R}$  to  $\text{CO}$  on In (101) and S-In (101) surfaces. (h) Gibbs free energies for the formation of  $\text{H}^*$  on pure In (101), In and S sites of S-In (101) surfaces. (i) Schematic illustration of the role of  $\text{S}^{2-}$  in promoting water dissociation and  $\text{H}^*$  formation for the reduction of  $\text{CO}_2$  to formate. Free energies of (d, e and f) are shown relative to gas  $\text{CO}_2$  and  $\text{H}_2$ . The green, yellow, gray, red, and blue balls represent In, S, O, C, and H (reprinted with permission from ref. 286. Copyright 2019, Nature Publishing Group).

optical coatings, and various other applications and have gained considerable interest.<sup>290</sup> Many morphologies of zinc sulfides, such as nanowires,<sup>291,292</sup> nanorods,<sup>293</sup> nanosheets,<sup>294</sup> nanotubes,<sup>295</sup> and other low-dimensional materials,<sup>296</sup> have been reported by researchers. However, the application of Zn-based sulfides and their derivatives as ECO<sub>2</sub>R catalysts is still limited.<sup>297–299</sup>

**2.8.1 Interfacial engineering.** Zhen *et al.*<sup>297</sup> synthesized ZnS/Zn electrode using sulfur infiltration techniques, demonstrating well-developed surface technology treatment. They found ZnS/Zn comprises three layers; ZnS is the upper layer, Zn is the substrate, and the transition layer in between (Fig. 20a). As shown from SEM images (Fig. 20b and c), this transition layer plays a significant role in strongly connecting the upper layer (ZnS) to the substrate (Zn) by offering more active sites. The current density was found to be stable at 6.72 mA cm<sup>-2</sup> at -2.4 V<sub>Fe/Fe<sup>c</sup></sub> with a faradaic efficiency (FE<sub>CO</sub>) of 92% for ECO<sub>2</sub>R in propylene carbonate/tetrabutylammonium perchlorate (PC/TBAP) electrolyte. In another work, Li and the group developed an exciting ECO<sub>2</sub>R catalyst by tailoring the Zn nanosheet surface with ZnS subnanometer layer. Notably, the S–Zn–S nanosheet electrodes exhibited high faradaic efficiency and outstanding stability. Its performance is better than all previously stated Zn-based catalysts and comparable to noble metal electrocatalysts. Experimental and theoretical studies showed that S atoms in S–Zn–S nanosheets modified the Zn nanosheet to provide higher adsorption capability of the \*COOH intermediate, improving CO<sub>2</sub> reduction and overturning the competing HER process. They found that S–Zn–S NSs achieved the highest FE of ~94.2% at -0.8 V vs. RHE for CO formation, which outperformed all Zn-based catalysts reported in the literature.<sup>298</sup> Recently, Song and co-workers fabricated ZnS/ZnO heterogeneous interfacial structure for improved CO<sub>2</sub> reduction

performance (Fig. 20d). The ZnS/ZnO interface structure (Fig. 20e) considerably increases the ECO<sub>2</sub>R performance (FE<sub>CO</sub> 98%) than ZnS (FE<sub>CO</sub> ~66%) and ZnO (FE<sub>CO</sub> ~88%) catalysts, presenting a promising approach for developing an inexpensive, stable, and high-performance catalyst.<sup>299</sup>

## 2.9 Titanium (Ti)-based sulfide

TiS<sub>2</sub> is a potential CO<sub>2</sub>-to-CO conversion option because of the cohesive van der Waals type of bonding structure with zero bandgaps similar to TMDs such as Mo and W and semimetal class with conductivity similar to graphite.<sup>300,301</sup> In 2020, Aljabour *et al.*<sup>302</sup> synthesized semi-metallic titanium disulfide (TiS<sub>2</sub>) using atomic layer deposition (ALD) methods. The catalyst exhibited exceptional cathodic energy efficiency of 64% and carbon conversion efficiencies, the combined faradaic efficiencies of 95% for CO and formate, with  $j_{\text{CO}} = 5 \text{ mA cm}^{-2}$  at -0.5 V<sub>RHE</sub>. *In situ* FTIR further revealed that sulfur and CO<sub>2</sub> are bound as monothiocarbonate intermediates, which kinetically favored the higher CO formation.

## 2.10 Other metal-based sulfides

Simon and the group used the microwave-assisted non-aqueous sol-gel method to synthesize phase-pure spinel Ni<sub>2</sub>FeS<sub>4</sub> nanosheets with a specific surface area of 80 m<sup>2</sup> g<sup>-1</sup>. They utilized metal acetylacetonates and benzyl mercaptan as a sulfur precursor. They found noble metal-free Ni<sub>2</sub>FeS<sub>4</sub> nanosheets electrochemically active for CO production from aqueous CO<sub>2</sub> at a potential of -0.7 V vs. RHE and CO product selectivity of 6.0% with a faradaic efficiency of 5.9%.<sup>303</sup> Similarly, Zhao *et al.*<sup>304</sup> developed FeS<sub>2</sub>/NiS nanocomposite electrocatalyst by simple hydrothermal synthesis. It was seen that active sites at the FeS<sub>2</sub> and NiS interface efficiently suppressed the HER and facilitated CO<sub>2</sub> reduction. The low-cost nanocomposite catalyst obtained a 64% FE for CO<sub>2</sub> to CH<sub>3</sub>OH. This research shows active sites at the FeS<sub>2</sub> and NiS interface suppressed the HER side reaction while promoting the ECO<sub>2</sub>R.

In 2018, Piontek and co-workers reported a low-cost, efficient bimetallic sulfide Fe<sub>4.5</sub>Ni<sub>4.5</sub>S<sub>8</sub> (pentlandite) for electrochemical water splitting and CO<sub>2</sub> reduction with solvent-dependent product selectivity. Interestingly, they found that using aprotic solvents such as acetonitrile, dimethylformamide, dimethyl sulfoxide, and propylene carbonate with well-defined water concentrations suppressed HER and favored ECO<sub>2</sub>R. The bimetallic sulfide presented a faradaic efficiency of 87% and 13% for CO and CH<sub>4</sub>, respectively, with a current density of 3 mA cm<sup>-2</sup>. The findings revealed that optimizing the availability of protons in the electrolyte–electrocatalyst interface was crucial for effective ECO<sub>2</sub>R.<sup>305</sup> Inspired by the work done by Tetzlaff *et al.*<sup>306</sup> with Fe/Ni ratio in Fe<sub>x</sub>Ni<sub>9-x</sub>S<sub>8</sub> for CO<sub>2</sub> electroreduction, Pellumbi *et al.*<sup>307</sup> explored the effect of S/Se by preparing bimetallic sulfide composite Fe<sub>4.5</sub>Ni<sub>4.5</sub>S<sub>8-y</sub>Se<sub>y</sub> (y = 1–5). The results demonstrated that the selectivity for CO increased as the Se percentage increased, and the maximum faradaic efficiency reached 84% with the composition Fe<sub>4.5</sub>Ni<sub>4.5</sub>S<sub>4</sub>Se<sub>4</sub>. The formation of the product was changed due to variation of average interatomic distances at the active sites. Briefly, with the

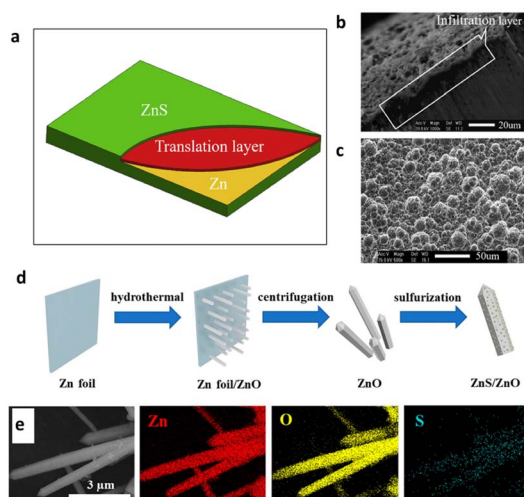


Fig. 20 (a) A schematic diagram of the infiltration layer (b and c) scanning electron microscopes image of ZnS electrode (reprinted with permission from ref. 297. Copyright 2018, Elsevier); (d) schematic diagram of the synthesis process of ZnS/ZnO catalyst; (e) SEM image and corresponding EDX elemental maps of ZnS/ZnO catalyst (reprinted with permission from ref. 299. Copyright 2021, American Chemical Society).



increasing Se concentration, the dimensions of the underlying crystal lattice and the metal–metal distances gradually increased, suppressing proton binding and promoting CO<sub>2</sub> binding. In 2023, Han and the collaborators<sup>308</sup> synthesized Cu/Ag(S) using electrochemical treatment derived from Cu/Ag<sub>2</sub>S/Ag, incorporating Cu single atom in Ag(S) defective sites. Consequently, the resulting yield and ECO<sub>2</sub>R faradaic efficiency (FE<sub>ECO<sub>2</sub>R</sub>) reach 93.0% at an ECO<sub>2</sub>R partial current density ( $j_{\text{ECO}_2\text{R}}$ ) of 2.9 mA cm<sup>-2</sup> under -1.0 V vs. RHE, respectively, showing a significant improvement as compared to that of sulfur-removed Ag<sub>2</sub>S/Ag without Cu SACs (Ag(S), 78.5% FE<sub>ECO<sub>2</sub>R</sub> with 1.8 mA cm<sup>-2</sup>  $j_{\text{ECO}_2\text{R}}$ ). The group, by *in situ* and *ex situ* characterizations together with theoretical calculations, proposed interaction between Cu SACs and their neighboring defective Ag surface increase microstrain and downshift the d-band center of Cu/Ag(S), thus lowering the energy barrier by ~0.5 eV for \*CO formation, which leads to the improved ECO<sub>2</sub>R activity and selectivity toward CO and C<sub>2+</sub> products.

However, for MS-based nanomaterials, S leaching was also widely observed during ECO<sub>2</sub>R. For example, CuS is not thermodynamically stable in the reduction process and can easily convert into metallic Cu, CuO, or Cu<sub>2</sub>O as per the observations from XPS and HRTEM analysis.<sup>126,139,151</sup> In this regard, Shinagawa *et al.*<sup>145</sup> did XPS and SAED analysis with the post-reaction sample. They demonstrated that during ECO<sub>2</sub>R cathodic environment induces the loss of excess sulfur in the catalysts and that the S-modified materials, irrespective of the initial sulfur content, can significantly affect the stability of the catalyst. Zhao *et al.*<sup>152</sup> employed XPS and HRTEM and demonstrated that in ECO<sub>2</sub>R, CuS nanosheets are partially reduced to metallic Cu, and the metallic Cu phase is partially oxidized to CuO after CO<sub>2</sub> electroreduction. Furthermore, Zhang and the collaborator employed XPS in their work and demonstrated CuS-HP electrocatalyst prepared from HKUST-1 was reconstructed to Cu(S) with a minimal S<sup>δ-</sup> (0 ≤ δ ≤ 2) in the derived catalysts. Further, they observed that despite having less S content, the polyhedron structures offer high activity and stability during the ECO<sub>2</sub>R.<sup>155</sup> In this context, the ECO<sub>2</sub>R mechanism on sulfur-modified Cu electrodes for highly selective formic acid (HCOOH) generation was investigated using experiment-based theoretical DFT modelling.<sup>309</sup> The stability of residual sulfur atoms was discovered to be highly dependent on their local environment and symmetry, with the majority of sulfur existing in relatively unstable forms that satisfy the experimentally observed negative XPS shift<sup>157</sup> and strong CO\* surface-enhanced infrared absorption spectroscopy signal.<sup>157,158</sup> At the early stages of ECO<sub>2</sub>R, the reduced S migrates from the Cu electrode to the electrode–electrolyte interface and CO\* readily forms at the Cu electrode surface. During this dynamic process, additional of reduced S and already formed CO\* appear at the interface due to a cooperation mechanism; that is, CO\* reduces the loss of sulfur by stabilizing the residual S at Cu electrode surface, increasing the CO\* coverage by enhancing CO\* adsorption. According to the DFT simulation, ECO<sub>2</sub>R energy diagrams revealed that these types of reduced S do not directly facilitate formic acid production but instead dominant CO\* production and strong CO\* adsorption. Theoretical study also confirms

that the strong CO\* adsorption caused by the sulfur atoms, increases CO\* coverage four times more than clean Cu surface. At the end of the reaction, surface reaction sites are blocked in the presence of the dense CO\* network, which leads to solution-phase CO<sub>2</sub> hydrogenation and favours highly selective HCOOH production.<sup>145,310</sup> Finally, a synergistic effect between residual S and CO\* to achieve dominant formic acid production for the electrochemical CO<sub>2</sub> reduction reaction is proposed by combining actual experimental observations from the literature and our DFT calculations. These findings detailed the fundamental understanding of the important role of S atoms in a highly selective CO<sub>2</sub> electroreduction mechanism on metallic Cu surfaces. Meanwhile, it should be noted that this S-modified Cu electrode is a thermodynamically metastable structure, and further S loss during the reactions could be hindered the mechanism for ECO<sub>2</sub>R towards HCOOH formation.<sup>309</sup>

Meanwhile, in work by Li *et al.*,<sup>191</sup> XPS results evidenced the negligible changes of the corresponding peak positions in Cd<sup>2+</sup> and the S<sup>2-</sup> XPS spectra of the initial and used electrocatalysts only with the reduced intensity. These findings support the stability of CdS nanorods during ECO<sub>2</sub>R. In another work published by Luo's group, SnS<sub>2</sub> monolayers were synthesized by a facile Li intercalation/exfoliation method. Later, the XRD analysis of the catalysts after electrolysis indicated that the SnS<sub>2</sub> monolayers were partially reduced to metallic Sn in the CO<sub>2</sub> electroreduction.<sup>232</sup> Like SnS<sub>2</sub>, defect-rich Bi<sub>2</sub>S<sub>3</sub> also tends to reduce metallic Bi during ECO<sub>2</sub>R; as observed by HRTEM analysis before and after electrolysis, Zhang *et al.*<sup>245</sup> exhibited a lattice fringe of 0.22 nm corresponding to (110) plane, suggesting the complete reduction of sulfide to crystalline Bi. A work by Chi *et al.*<sup>284</sup> illustrated a loss of excess S content for In<sub>2</sub>S<sub>3</sub> during ECO<sub>2</sub>R. A combined XPS and SEM-EDX results demonstrate that the stability degradation of In<sub>2</sub>S<sub>3</sub> can be attributable to S leaching. Pander *et al.*<sup>288</sup> elucidated from XPS studies that the PbS would be partially reduced to metallic Pb in ECO<sub>2</sub>R, and the metallic Pb phase could be further partially oxidized to PbO after electrochemical CO<sub>2</sub> reduction. Further, for most of the MS-based nanomaterials, it was observed that during ECO<sub>2</sub>R S<sup>2-</sup> ions were released into the electrolyte and absorbed on the surface of catalysts, suppressing the formation of other hydrocarbon products and resulting in high selectivity towards HCOOH.<sup>151,153,309</sup> Hence, the method of stabilizing MS-based nanomaterials in the catalytic process without converting them to their metallic and oxide counterparts needs to be explored.

As described in Section 2.1, a variety of strategies have been implemented to control catalyst deactivation (*i.e.*, corrosion and dissolution) and increase the stability and selectivity of MS-based nanomaterials for ECO<sub>2</sub>R, including (i) doping, coupling, or loading a passive metal on the semiconductor surface, which acts as a co-catalyst to enhance the rate of electrochemical CO<sub>2</sub> reduction and (ii) tune or alteration of the semiconductor surface with a metal oxide, carbon-based material, or a polymer (iii) using techniques for nanostructuring to change the electrode's surface. These research efforts are aimed at improving the ECO<sub>2</sub>R performance and stability of earth-abundant MS-based nanomaterials. The

Table 3 A summary of recently reported best-performing data for carbon-based ECO<sub>2</sub>R catalysts

Products	Electrode	Potential	Electrolyte	Reactor	Current density (mA cm <sup>-2</sup> )	FE (%)	Stability (h)	Ref.
HCOOH	Sn/OMC-GDE	-0.86 V <sub>RHE</sub>	0.5 M KHCO <sub>3</sub>	Flow cell	80.12	97.4	—	311
	In SACs-1000	-0.79 V <sub>RHE</sub>	0.5 M KHCO <sub>3</sub>	H-cell	6.8	85.2	14	312
CH <sub>3</sub> OH	Cu-SAs/TCNFs	-0.90 V <sub>RHE</sub>	0.1 M KHCO <sub>3</sub>	H-cell	90	44	50	313
Ethanol	Fe- <i>n</i> -f-CNTs	-0.80 V <sub>RHE</sub>	0.5 M KHCO <sub>3</sub>	H-cell	25	45	—	314
CH <sub>4</sub>	SA-Zn/MNC	-1.80 V <sub>RHE</sub>	1 M KHCO <sub>3</sub>	H-cell	31.8	85	35	315
	Cu-N-C-800	-1.40 V <sub>RHE</sub>	0.1 M KHCO <sub>3</sub>	H-cell	10.6	38.7	10	316
CO	Fe <sub>1</sub> N <sub>2</sub> O <sub>2</sub> /NC	-0.50 V <sub>RHE</sub>	0.1 M KHCO <sub>3</sub>	H-cell	2.5	99.7	12	317
	Bi-SAs-NS/C	-0.80 V <sub>RHE</sub>	0.5 M KHCO <sub>3</sub>	H-cell	10.24	98.3	24	318
	Sn-NOC	-0.70 V <sub>RHE</sub>	0.1 M KHCO <sub>3</sub>	H-cell	14.81	94	8	319
	NiSA-N <sub>x</sub> -C	-0.80 V <sub>RHE</sub>	0.5 M KHCO <sub>3</sub>	H-cell	12	98	10	320
	Fe-SA/BNC	-0.70 V <sub>RHE</sub>	0.1 M KHCO <sub>3</sub>	H-cell	2	94	30	321
	A-Ni/CMK	0.80 V <sub>RHE</sub>	1 M KOH	Flow cell	366	95	5	322
	Ni SAs-NCW	-0.43 V <sub>RHE</sub>	1 M KOH	Flow cell	41.6	95.4	4	323
	Ni-N/PC	-0.40 V <sub>RHE</sub>	1 M KOH	Flow cell	100	98	72	324
	CoPc/NH <sub>2</sub> -CNT	-0.60 V <sub>RHE</sub>	1 M KOH	Flow cell	225	100	100	325
	Ni-NC 60% PTFE	-2.73 V <sub>RHE</sub>	1 M Cs <sub>2</sub> SO <sub>4</sub>	Flow cell	250	100	36	326
	Ni-SAC-CNT	-0.35 V <sub>RHE</sub>	1 M KOH	Flow cell	400	99	8	327
	Cu-N-CNT	-0.82 V <sub>RHE</sub>	1 M KOH	Flow cell	234.3	95.7	25	328
	Ni-N <sub>4-x</sub> C <sub>x</sub>	-0.34 V <sub>RHE</sub>	1 M KOH	Flow cell	300	99.4	6	329
	Fe-NC-Q	-0.40 V <sub>RHE</sub>	1 M KOH	Flow cell	121	99	10	330
	Ni DSC	-1.20 V <sub>RHE</sub>	1 M KHCO <sub>3</sub>	Flow cell	150	94.3	50	331
CoN <sub>4</sub> -CNT	-1.70 V <sub>RHE</sub>	1 M KOH	Flow cell	350	99.8	8	332	

results of prior studies and the performance data for various MS-based nanomaterials were summarized in Table 2. It was noted from Table 2 that certain MS-based electrocatalysts have shown excellent partial current density and faradaic efficiency, as well as suitable levels of stability during the ECO<sub>2</sub>R. Besides, to compare the catalytic performance of MS-based nanomaterials focusing on partial current density and faradaic efficiency, recent best-performing carbon-based and copper-based ECO<sub>2</sub>R catalysts are reported in Tables 3 and 4, respectively. For instance, CuS/BM coated with PTFE,<sup>154</sup> Sulfur modulated tin catalysts (Sn(S)/Au),<sup>229</sup> SnS/aminated-C,<sup>230</sup> S doped-Bi<sub>2</sub>O<sub>3</sub>-CNT,<sup>244</sup> in nanoparticles on In<sub>2</sub>S<sub>3</sub> nanosheets,<sup>282</sup> ZnIn<sub>2</sub>S<sub>4</sub>,<sup>284</sup> sulfur-doped indium<sup>286</sup> have been exhibited better current density and faradaic efficiency for HCOOH formation as compared to copper-based and carbon-based catalyst. In addition, porous Cd modified by sulfur,<sup>183</sup> Cadmium sulfide (CdS) nanoneedle arrays,<sup>184</sup> Bulk MoS<sub>2</sub> with Mo-terminated edge,<sup>256</sup> rGO-PEI-MoS<sub>2</sub>,<sup>263</sup> 5% Nb-doped on vertically oriented MoS<sub>2</sub>,<sup>268</sup> ZnS/ZnO Interface<sup>299</sup> exhibited good performance in terms of current density and faradaic efficiency than a copper-based catalyst, for CO production. Meanwhile from Tables 3 and 4, it has been observed that carbon-based catalyst showed better CO current density (<100 mA cm<sup>-2</sup>) in flow-cell as compared to MS-based nanomaterials. For other products (*i.e.*, C<sub>2+</sub> and CH<sub>4</sub>) Copper-based catalysts exhibited superior performance than MS-based nanomaterials.

### 3 Summary and future prospects

Metal sulfide-based nanomaterials have been the focus of significant scientific and technical importance due to their high electrocatalytic activity for ECO<sub>2</sub>R. In this review: the

electrochemical and morphological characteristics of these materials have been compared, and the relationship between structure and electrocatalytic properties has been highlighted, evaluating how it is possible to tune the composition, the active site nature, and the framework of the catalyst for ECO<sub>2</sub>R applications. The recent advancement summarized below:

(1) We have shown the concentration of S in MS-based nanomaterials can enhance the activity of ECO<sub>2</sub>R catalysts. Furthermore, incorporating S significantly changes reaction intermediates' adsorption/binding energy, thereby improving catalytic performance.

(a) The MS-based nanomaterials exhibited optimum catalytic performance due to the synergy between S and metals' active sites. According to the literature survey of single metals, Cd, Mo, and Zn tends to produce CO, whereas optimizing the electronic structure of metal atoms by introducing S can enhance charge density around the metal atoms, hence facilitating the capture and electroreduction process towards CO<sub>2</sub>.

(b) The incorporated defect and interface engineering of S-derived catalysts accelerate charge density distributions on the catalyst surface, thereby tuning the intermediates' free energy and improving the overall catalytic performance.

(2) The chalcogen elements (S, Se) in MS-based nanomaterials are believed to influence the active sites, resulting in high activity and selectivity of ECO<sub>2</sub>R. For instance, Sargent group<sup>229</sup> reported that the existence of S atoms on the Sn catalyst surface could promote undercoordinated sites, resulting in improving the ECO<sub>2</sub>R to formate selectivity. They have shown by doping S atoms into Sn, the Sn atom near the S atom is responsible for ECO<sub>2</sub>R, significantly reducing the free energy of formate production, and improving the overall catalytic performance. Similarly, Xie and collaborators<sup>276</sup> reported that

Table 4 A summary of recently reported best-performing data for copper-based ECO<sub>2</sub>R catalysts

Products	Electrode	Potential	Electrolyte	Reactor	Current density (mA cm <sup>-2</sup> )	FE (%)	Stability (h)	Ref.
C <sub>2+</sub>	Cu nanocubes	-0.7 V <sub>RHE</sub>	0.25 M KHCO <sub>3</sub>	H-cell	$j_{C_{2+}} = 41$	60.5	2	333
	Cu <sub>3</sub> N	-1.15 V <sub>RHE</sub>	1 M KOH	Flow cell	$j_{C_{2+}} = 1100$	73.7	6	334
	Defect-site-rich Cu catalyst	-1.02 V <sub>RHE</sub>	0.1 M KHCO <sub>3</sub>	Flow cell	$j_{C_{2+}} > 100$	70	30	335
	Cu-CuI composite catalyst	-0.87 V <sub>RHE</sub>	1 M KOH	Flow cell	591	71	85	336
	Cu (OH) <sub>2</sub> -D/Cu	-0.54 V <sub>RHE</sub>	0.1 M NaHCO <sub>3</sub>	Flow cell	217	~87	11	337
	(100)-rich Cu	-0.63 V <sub>RHE</sub>	0.1 M NaHCO <sub>3</sub>	Flow cell	320	88	65	338
	Cu@C-0.4	-0.7 V <sub>RHE</sub>	0.1 M KHCO <sub>3</sub>	Flow cell	1.23	91	16	339
	C <sub>2</sub> H <sub>4</sub>	Activated Cu nanowires	-1.01 V <sub>RHE</sub>	0.1 M KHCO <sub>3</sub>	H-cell	~17.3	77	~200
Star decahedron Cu NPs		-0.993 V <sub>RHE</sub>	0.1 M KHCO <sub>3</sub>	H-cell	17	52.43	12	341
Cu nanosheets with nano-scaled defects		-1.2 V <sub>RHE</sub>	0.1 M K <sub>2</sub> SO <sub>4</sub>	RRDE	60	83.2	14	342
Cu-Al		-0.5 V <sub>RHE</sub>	1 M KOH	Flow cell	400	80	100	343
CO	Cu <sub>2</sub> Sb decorated Cu nanowire arrays	-0.90 V <sub>RHE</sub>	0.1 M KHCO <sub>3</sub>	H-cell	—	86.5	12	344
	Ni-Cu dual atom catalysts	-0.6 V <sub>RHE</sub>	0.5 M KHCO <sub>3</sub>	H-cell	95.21	97.7	—	345
CH <sub>3</sub> OH	Cu SA/MXene	-1.4 V <sub>RHE</sub>	0.1 M KHCO <sub>3</sub>	H-cell	21.3	59.1	30	346
	Cu <sub>2-x</sub> Se	-2.1 V <sub>Ag/Ag<sup>+</sup></sub>	[Bmim]PF <sub>6</sub> -CH <sub>3</sub> CN-H <sub>2</sub> O	H-cell	41.5	77.6	25	347
CH <sub>4</sub>	Cu-MOF-74/Cu NPs	-1.3 V <sub>RHE</sub>	0.1 M KHCO <sub>3</sub>	H-cell	10.9	>50	4	348
	Cu/p-Al <sub>2</sub> O <sub>3</sub> SAC	-1.2 V <sub>RHE</sub>	1 M KOH	Flow cell	153	62	—	349
HCOOH	Cu <sub>3</sub> P NS/Cu	-0.1 V <sub>RHE</sub>	0.1 M KHCO <sub>3</sub>	Flow cell	—	90	16	350
	In <sub>1.5</sub> Cu <sub>0.5</sub> NPs	-1.2 V <sub>RHE</sub>	0.1 M KHCO <sub>3</sub>	H-cell	3.59	90	5	351

doping Se atoms in MoS<sub>2</sub>, enhanced MoS<sub>2</sub>'s ECO<sub>2</sub>R selectivity. DFT calculations revealed that the active site of the ECO<sub>2</sub>R is the Mo atom. Adding Se atoms to the system, shortens the MoS bonds, lowering the \*CO adsorption energy and improving selectivity for CO production. According to their findings, chalcogen elements in MS-based materials can improve ECO<sub>2</sub>R activity and selectivity by adjusting the adsorption energy of reaction intermediates (\*COOH and \*CO).

(3) The morphology and electrocatalytic properties of metal-sulfides differ significantly from those of their corresponding bare metals. For example, pure metal Mo often exhibits no ECO<sub>2</sub>R activity. MoS<sub>2</sub>, on the other hand, has a layered structure and can efficiently activate the ECO<sub>2</sub>R to CO conversion because the layered structure of MoS<sub>2</sub> can offer more catalytic active sites that lead to the Gibbs free energy changing for intermediate formation. Cu is a commonly used ECO<sub>2</sub>R catalyst with high selectivity for producing methane and ethylene. However, S-derived and S-doped copper catalyst mainly produces HCOOH and H<sub>2</sub>. Sn exhibits high faradaic efficiency, selectivity, and stability for the formation of HCOOH. In contrast, atomically thin layer SnS shows improved activity during ECO<sub>2</sub>R.

Despite its numerous advantages, some key challenges, such as a fundamental understanding of the role of S on materials properties and low catalytic performances (*i.e.*, selectivity and stability, and ambiguity), must be considered. The following research directions can be proposed to address these limitations:

(1) Investigating new MS-based nanomaterials catalysts through novel synthesis and modification methods. Although there are promising developments in the design of catalysts and overall improvement of the ECO<sub>2</sub>R process, the catalytic efficiency and product selectivity are still very low. Therefore, more research is required to identify a new class of MS-based nanomaterials. For instance, there are various forms of bismuth,

such as single metal, oxide, and oxyhalide with an ordinary 2D structure, which is an attractive material due to its economic and high selectivity for HCOOH production in ECO<sub>2</sub>R. However, Bi-sulfide-based materials have not been thoroughly investigated, and additional research is required. An earlier research work studied the role of defect-rich structure and specific interfacial phenomena between Bi<sub>2</sub>S<sub>3</sub>-Bi<sub>2</sub>O<sub>3</sub> interfaces,<sup>246</sup> which can motivate further research into the effect of sulfur composition on product selectivity, the design of a 2D framework structure with particle size optimization, heteroatom-doping, and so forth. In addition, the electrocatalytic activity of other metal-sulfides, *i.e.*, Lead, zinc, iron, cobalt, and nickel, during ECO<sub>2</sub>R should also be further studied. Although this review highlighted the critical advances in interfacial effect and facet promotion, more attention should focus on the strategy development of material doping, composition, and coupling substrate. In this regard, exploring new synthesis methods on highly efficient ECO<sub>2</sub>R electrocatalysts would be beneficial.

(2) In order to catalyze the ECO<sub>2</sub>R activity in terms of selectivity and stability of MS-based nanomaterials, it is necessary to conduct experimental and theoretical studies to have a better understanding of the role of the S group during the process. For example, the catalyst must be well characterized before increasing the S content to understand the S's local chemical environment comprehensively. Additionally, in order to understand the general trend among the oxygen group elements, it is also required to compare S-derived catalysts with O-derived or new catalysts. Finally, considering the different chemical and physical properties of catalysts, it should be investigated further whether their outstanding electrochemical performance can be attributed to defects or residual S.

(3) Improving product selectivity and catalyst stability of MS-based nanomaterials during ECO<sub>2</sub>R. The ECO<sub>2</sub>R catalytic selectivity of most MS-based nanomaterials is relatively unitary,

the faradaic efficiency of CO and HCOOH is high as summarized in Table 2, and other products (C<sub>1</sub> and C<sub>2</sub> products) are challenging to be produced. For commercial electrochemical CO<sub>2</sub> conversion, achieving high-energy-dense C<sub>2</sub> products is crucial. However, there are few research findings on the selective formation of C<sub>1</sub> products (such as CH<sub>4</sub> and CH<sub>3</sub>OH) and C<sub>2</sub> products (C<sub>2</sub>H<sub>4</sub> and EtOH). In contrast, CO and HCOOH are the main products of Cu-sulfide-based, bimetallic and other MS-based catalysts. Therefore, more research is needed to investigate the use of MS-based nanomaterial in forming a wide range of products with high selectivity. More importantly, a long-term stability analysis is recommended to investigate the catalyst's poisoning or degradation, which is critical for the design and development of the catalyst.

(4) Finding the fundamental understanding of electrochemical reaction pathways through experimental and theoretical approaches. It is necessary to clarify the reaction mechanism with theoretical modelling and simulation and establish the structure–activity relationship to guide the subsequent catalyst structure design. Several literature reports show that DFT is an efficient tool for calculating reaction intermediates' energy values. However, it is well established that the theoretically predicted processes may differ with different DFT models. Furthermore, some calculations were shown to be theoretically feasible without experimental support. Thus, DFT analyses should be closely coupled with experiments to validate their feasibility for understanding reaction mechanisms. Some advanced characterization techniques, such as *in situ* electrochemical-spectroscopic methods, need to be developed, including *in situ* or operando electrochemical XRD, FTIR, Raman, XPS, synchrotron methods, *etc.*, to a better understanding of the reaction mechanisms.

## Conflicts of interest

There are no conflicts to declare.

## Acknowledgements

The authors gratefully acknowledge Birla Institute of Technology, Mesra for providing institute research fellowship and I-STEM/catalytic grant/acad\_18/2022-2023 for the financial support.

## References

- S. J. Davis, K. Caldeira and H. D. Matthews, *Science*, 2010, **329**, 1330–1333.
- M. I. Hoffert, *Science*, 2010, **329**, 1292–1294.
- L. I. Eide, M. Batum, T. Dixon, Z. Elamin, A. Graue, S. Hagen, S. Hovorka, B. Nazarian, P. H. Nøkleby, G. I. Olsen, P. Ringrose and R. A. M. Vieira, *Energies*, 2019, **12**, 1945.
- P. Falkowski, R. J. Scholes, E. Boyle, J. Canadell, D. Canfield, J. Elser, N. Gruber, K. Hibbard, P. Hogberg, S. Linder, F. T. Mackenzie, B. Moore, T. Pedersen, Y. Rosental, S. Seitzinger, V. Smetacek and W. Steffen, *Science*, 2000, **290**, 291–296.
- B. M. Tackett, E. Gomez and J. G. Chen, *Nat. Catal.*, 2019, **2**, 381–386.
- K. Teramura, S. Iguchi, Y. Mizuno, T. Shishido and T. Tanaka, *Angew. Chem., Int. Ed.*, 2012, **51**, 8008–8011.
- H. Homayoni, W. Chanmanee, N. R. de Tacconi, B. H. Dennis and K. Rajeshwar, *J. Electrochem. Soc.*, 2015, **162**, E115–E122.
- M. Li, E. Irtem, H.-P. Iglesias van Montfort, M. Abdinejad and T. Burdyny, *Nat. Commun.*, 2022, **131**(13), 1–11.
- J. Guan, S. A. Berlinger, X. Li, Z. Chao, V. Sousa e Silva, S. Banta and A. C. West, *J. Biotechnol.*, 2017, **245**, 21–27.
- R. Kortlever, I. Peters, S. Koper and M. T. M. Koper, *ACS Catal.*, 2015, **5**, 3916–3923.
- M. Abdinejad, A. Seifitokaldani, C. Dao, E. H. Sargent, X. A. Zhang and H. B. Kraatz, *ACS Appl. Energy Mater.*, 2019, **2**, 1330–1335.
- M. Abdinejad, C. Dao, B. Deng, F. Dinic, O. Voznyy, X. A. Zhang and H. B. Kraatz, *ACS Sustain. Chem. Eng.*, 2020, **8**, 9549–9557.
- Z. Liang, J. Wang, P. Tang, W. Tang, L. Liu, M. Shakouri, X. Wang, J. Llorca, S. Zhao, M. Heggen, R. E. Dunin-Borkowski, A. Cabot, H. Bin Wu and J. Arbiol, *Appl. Catal. B Environ.*, 2022, **314**, 121451.
- D. Kim, C. S. Kley, Y. Li and P. Yang, *Proc. Natl. Acad. Sci. U. S. A.*, 2017, **114**, 10560–10565.
- Y. C. Li, Z. Wang, T. Yuan, D. H. Nam, M. Luo, J. Wicks, B. Chen, J. Li, F. Li, F. P. G. De Arquer, Y. Wang, C. T. Dinh, O. Voznyy, D. Sinton and E. H. Sargent, *J. Am. Chem. Soc.*, 2019, **141**, 8584–8591.
- R. A. Geioushy, M. M. Khaled, K. Alhooshani, A. S. Hakeem and A. Rinaldi, *Electrochim. Acta*, 2017, **245**, 456–462.
- A. Hasani, M. A. Teklagne, H. H. Do, S. H. Hong, Q. Van Le, S. H. Ahn and S. Y. Kim, *Carbon Energy*, 2020, **2**, 158–175.
- J. Liu, C. Guo, A. Vasileff and S. Qiao, *Small Methods*, 2017, **1**.
- P. Saha, S. Amanullah and A. Dey, *Acc. Chem. Res.*, 2022, **55**, 134–144.
- G. F. Manbeck and E. Fujita, *J. Porphyr. Phthalocyanines*, 2015, **19**, 45–64, DOI: [10.1142/S1088424615300013](https://doi.org/10.1142/S1088424615300013).
- P. R. Yaashikaa, P. Senthil Kumar, S. J. Varjani and A. Saravanan, *J. CO<sub>2</sub> Util.*, 2019, **33**, 131–147.
- A. Bagger, W. Ju, A. S. Varela, P. Strasser and J. Rossmeisl, *ChemPhysChem*, 2017, **18**, 3266–3273.
- M. Todoroki, K. Hara, A. Kudo and T. Sakata, *J. Electroanal. Chem.*, 1995, **394**, 199–203.
- G. O. Larrazábal, A. J. Martín, S. Mitchell, R. Hauert and J. Pérez-Ramírez, *ACS Catal.*, 2016, **6**, 6265–6274.
- B. Ávila-Bolívar, L. García-Cruz, V. Montiel and J. Solla-Gullón, *Molecules*, 2019, **24**, 2032.
- Q. Li, J. Fu, W. Zhu, Z. Chen, B. Shen, L. Wu, Z. Xi, T. Wang, G. Lu, J. J. Zhu and S. Sun, *J. Am. Chem. Soc.*, 2017, **139**, 4290–4293.
- G. B. Damas, C. R. Miranda, R. Sgarbi, J. M. Portela, M. R. Camilo, F. H. B. Lima and C. M. Araujo, *Catal.*, 2019, **9**, 636.

- 28 W. Zhu, R. Michalsky, Ö. Metin, H. Lv, S. Guo, C. J. Wright, X. Sun, A. A. Peterson and S. Sun, *J. Am. Chem. Soc.*, 2013, **135**, 16833–16836.
- 29 W. Zhu, Y. J. Zhang, H. Zhang, H. Lv, Q. Li, R. Michalsky, A. A. Peterson and S. Sun, *J. Am. Chem. Soc.*, 2014, **136**, 16132–16135.
- 30 K. Sun, L. Wu, W. Qin, J. Zhou, Y. Hu, Z. Jiang, B. Shen and Z. Wang, *J. Mater. Chem. A*, 2016, **4**, 12616–12623.
- 31 R. Wang, H. Haspel, A. Pustovarenko, A. Dikhtiarenko, A. Russkikh, G. Shterk, D. Osadchii, S. Ould-Chikh, M. Ma, W. A. Smith, K. Takanabe, F. Kapteijn and J. Gascon, *ACS Energy Lett.*, 2019, **4**, 2024–2031.
- 32 D. Hye Won, H. Shin, J. Koh, J. Chung, H. ee Sang Lee, H. Kim, S. Ihl Woo, D. H. Won, J. Chung, H. S. Lee, S. I. Woo, H. Shin, J. Koh and H. Kim, *Angew. Chem.*, 2016, **128**, 9443–9446.
- 33 W. Luo, J. Zhang, M. Li and A. Züttel, *ACS Catal.*, 2019, **9**, 3783–3791.
- 34 A. Klinkova, P. De Luna, C. T. Dinh, O. Voznyy, E. M. Larin, E. Kumacheva and E. H. Sargent, *ACS Catal.*, 2016, **6**, 8115–8120.
- 35 J. Zeng, W. Zhang, Y. Yang, D. Li, X. Yu and Q. Gao, *ACS Appl. Mater. Interfaces*, 2019, **11**, 33074–33081.
- 36 S. Pérez-Rodríguez, G. García, L. Calvillo, V. Celorrio, E. Pastor and M. J. Lázaro, *Int. J. Electrochem.*, 2011, **2011**, 1–13.
- 37 M. Umeda, Y. Niitsuma, T. Horikawa, S. Matsuda and M. Osawa, *ACS Appl. Energy Mater.*, 2020, **3**, 1119–1127.
- 38 F. A. Hanc-Scherer, M. A. Montiel, V. Montiel, E. Herrero and C. M. Sánchez-Sánchez, *Phys. Chem. Chem. Phys.*, 2015, **17**, 23909–23916.
- 39 T. Mizuno, M. Kawamoto, S. Kaneco and K. Ohta, *Electrochim. Acta*, 1998, **43**, 899–907.
- 40 R. Kortlever, J. Shen, K. J. P. Schouten, F. Calle-Vallejo and M. T. M. Koper, *J. Phys. Chem. Lett.*, 2015, **6**, 4073–4082.
- 41 Y. Hori, in *Modern Aspects of Electrochemistry*, Springer, New York, 2008, pp. 89–189.
- 42 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. Nørskov, T. F. Jaramillo and I. Chorkendorff, *Chem. Rev.*, 2019, **119**, 7610–7672.
- 43 E. Tayyebi, J. Hussain, Y. Abghoui and E. Skúlason, *J. Phys. Chem. C*, 2018, **122**, 10078–10087.
- 44 N. Atrak, E. Tayyebi and E. Skúlason, *Appl. Surf. Sci.*, 2021, **570**, 151031.
- 45 H. Chen, A. D. Handoko, T. Wang, J. Qu, J. Xiao, X. Liu, D. Legut, Z. Wei Seh and Q. Zhang, *ChemSusChem*, 2020, **13**, 5690–5698.
- 46 K. Kannan, M. H. Sliem, A. M. Abdullah, K. K. Sadasivuni and B. Kumar, *Catalysts*, 2020, **10**, 549.
- 47 Y. Ji, J. K. Nørskov and K. Chan, *J. Phys. Chem. C*, 2019, **123**, 4256–4261.
- 48 S. Kang, S. Ju, S. Han and Y. Kang, *J. Phys. Chem. C*, 2020, **124**, 25812–25820.
- 49 M. Abdinejad, C. Dao, X. an Zhang and H. B. Kraatz, *J. Energy Chem.*, 2021, **58**, 162–169.
- 50 M. Abdinejad, L. F. B. Wilm, F. Dielmann and H. B. Kraatz, *ACS Sustain. Chem. Eng.*, 2021, **9**, 521–530.
- 51 M. Abdinejad, I. Santos da Silva and H. B. Kraatz, *J. Mater. Chem. A*, 2021, **9**, 9791–9797.
- 52 M. Abdinejad, Z. Mirza, X. A. Zhang and H. B. Kraatz, *ACS Sustain. Chem. Eng.*, 2020, **8**, 1715–1720.
- 53 M. Li, K. Yang, M. Abdinejad, C. Zhao and T. Burdyny, *Nanoscale*, 2022, **14**, 11892–11908.
- 54 M. Abdinejad, M. K. Motlagh, M. Noroozifar and H. B. Kraatz, *Mater. Adv.*, 2022, **3**, 1224–1230.
- 55 M. Abdinejad, C. Ferrag, M. N. Hossain, M. Noroozifar, K. Kerman and H. B. Kraatz, *J. Mater. Chem. A*, 2021, **9**, 12870–12877.
- 56 J. Qiao, Y. Liu, F. Hong and J. Zhang, *Chem. Soc. Rev.*, 2014, **43**, 631–675.
- 57 X. Liu, J. Xiao, H. Peng, X. Hong, K. Chan and J. K. Nørskov, *Nat. Commun.*, 2017, **8**, 1–7.
- 58 Q. Kong, X. An, Q. Liu, L. Xie, J. Zhang, Q. Li, W. Yao, A. Yu, Y. Jiao and C. Sun, *Mater. Horiz.*, 2023, **10**, 698–721.
- 59 W. Sun, X. Zhao, E. Webb, G. Xu, W. Zhang and Y. Wang, *J. Mater. Chem. A*, 2023, **11**(5), 2092–2127.
- 60 M. Abdinejad, T. Yuan, K. Tang, S. Duangdangchote, A. Farzi, H.-P. Iglesias van Montfort, M. Li, J. of Middelkoop, M. of Wolff, A. Seifitokaldani, O. Voznyy, T. Burdyny, J. Middelkoop, M. Wolff, P. Thomas Burdyny and P. Oleksandr Voznyy, *Chem. – A Eur. J.*, 2023, **29**(14), e202203977.
- 61 W. Wang, L. Shang, G. Chang, C. Yan, R. Shi, Y. Zhao, G. I. N. Waterhouse, D. Yang and T. Zhang, *Adv. Mater.*, 2019, **31**, 1808276.
- 62 Q. Ding, B. Song, P. Xu and S. Jin, *Chem*, 2016, **1**, 699–726.
- 63 L. Zeng, J. Shi, J. Luo and H. Chen, *J. Power Sources*, 2018, **398**, 83–90.
- 64 Y. Zhang, L. Hu and W. Han, *J. Mater. Chem. A*, 2018, **6**, 23610–23620.
- 65 L. Hu, Y. Zhang and W. Han, *New J. Chem.*, 2019, **43**, 3269–3272.
- 66 Y. Dong, S. Yang, Z. Zhang, J. M. Lee and J. A. Zapien, *Nanoscale*, 2018, **10**, 3159–3165.
- 67 Y. Dong, M. Hu, Z. Zhang, J. A. Zapien, X. Wang and J. M. Lee, *Nanoscale*, 2018, **10**, 13343–13350.
- 68 M. Chhowalla, H. S. Shin, G. Eda, L. J. Li, K. P. Loh and H. Zhang, *Nat. Chem.*, 2013, **54**(5), 263–275.
- 69 M. Wang, L. Zhang, Y. He and H. Zhu, *J. Mater. Chem. A*, 2021, **9**, 5320–5363.
- 70 J. Joo, T. Kim, J. Lee, S. Il Choi and K. Lee, *Adv. Mater.*, 2019, **31**, 1806682.
- 71 Y. Guo, T. Park, J. W. Yi, J. Henzie, J. Kim, Z. Wang, B. Jiang, Y. Bando, Y. Sugahara, J. Tang and Y. Yamauchi, *Adv. Mater.*, 2019, **31**, 1807134.
- 72 P. Kulkarni, S. K. Nataraj, R. G. Balakrishna, D. H. Nagaraju and M. V. Reddy, *J. Mater. Chem. A*, 2017, **5**, 22040–22094.
- 73 G. Giuffredi, T. Asset, Y. Liu, P. Atanassov and F. Di Fonzo, *ACS Mater. Au*, 2021, **1**, 6–36.
- 74 S. L. Li, K. Tsukagoshi, E. Orgiu and P. Samori, *Chem. Soc. Rev.*, 2015, **45**, 118–151.

- 75 S. Chandrasekaran, L. Yao, L. Deng, C. Bowen, Y. Zhang, S. Chen, Z. Lin, F. Peng and P. Zhang, *Chem. Soc. Rev.*, 2019, **48**, 4178–4280.
- 76 J. A. Dahl, B. L. S. Maddux and J. E. Hutchison, *Chem. Rev.*, 2007, **107**, 2228–2269.
- 77 S. Eustis and M. A. El-Sayed, *Chem. Soc. Rev.*, 2006, **35**, 209–217.
- 78 H. Şengül, T. L. Theis and S. Ghosh, *J. Ind. Ecol.*, 2008, **12**, 329–359.
- 79 L. Zeng, L. Tao, C. Tang, B. Zhou, H. Long, Y. Chai, S. P. Lau and Y. H. Tsang, *Sci. Rep.*, 2016, **6**, 1–8.
- 80 J. Tao, J. Chai, X. Lu, L. M. Wong, T. I. Wong, J. Pan, Q. Xiong, D. Chi and S. Wang, *Nanoscale*, 2015, **7**, 2497–2503.
- 81 Y. Zhong, X. Qiu, D. Chen, N. Li, Q. Xu, H. Li, J. He and J. Lu, *ACS Appl. Mater. Interfaces*, 2016, **8**, 28671–28677.
- 82 A. Jagadale, X. Zhou, D. Blaisdell and S. Yang, *Sci. Rep.*, 2018, **8**, 1–11.
- 83 M. S. M. Saifullah, M. Asbahi, M. Binti-Kamran Kiyani, S. Tripathy, E. A. H. Ong, A. Ibn Saifullah, H. R. Tan, T. Dutta, R. Ganesan, S. Valiyaveetil and K. S. L. Chong, *ACS Nano*, 2017, **11**, 9920–9929.
- 84 C. B. Roxlo, H. W. Deckman, J. Gland, S. D. Cameron and R. R. Chianelli, *Science*, 1987, **235**, 1629–1631.
- 85 A. Ambrosi, X. Chia, Z. Sofer and M. Pumera, *Electrochem. Commun.*, 2015, **54**, 36–40.
- 86 A. Kaltzoglou, P. Vaqueiro, T. Barbier, E. Guilmeau and A. V. Powell, *J. Electron. Mater.*, 2014, **43**, 2029–2034.
- 87 D. Voiry, H. Yamaguchi, J. Li, R. Silva, D. C. B. Alves, T. Fujita, M. Chen, T. Asefa, V. B. Shenoy, G. Eda and M. Chhowalla, *Nat. Mater.*, 2013, **12**, 850–855.
- 88 Y. Chen, J. Xi, D. O. Dumcenco, Z. Liu, K. Suenaga, D. Wang, Z. Shuai, Y. S. Huang and L. Xie, *ACS Nano*, 2013, **7**, 4610–4616.
- 89 J. Liu, Z. Zeng, X. Cao, G. Lu, L.-H. Wang, Q.-L. Fan, W. Huang and H. Zhang, *Small*, 2012, **8**, 3517–3522.
- 90 H. S. S. Ramakrishna Matte, A. Gomathi, A. K. Manna, D. J. Late, R. Datta, S. K. Pati and C. N. R. Rao, *Angew. Chem., Int. Ed.*, 2010, **49**, 4059–4062.
- 91 M. Abdinejad, K. Tang, C. Dao, S. Saedy and T. Burdyny, *J. Mater. Chem. A*, 2022, **10**, 7626–7636.
- 92 K. Kang, S. Xie, L. Huang, Y. Han, P. Y. Huang, K. F. Mak, C. J. Kim, D. Muller and J. Park, *Nature*, 2015, **520**, 656–660.
- 93 S. Zheng, L. Sun, T. Yin, A. M. Dubrovkin, F. Liu, Z. Liu, Z. X. Shen and H. J. Fan, *Appl. Phys. Lett.*, 2015, **106**, 063113.
- 94 E. Thimsen, S. V. Baryshev, A. B. F. Martinson, J. W. Elam, I. V. Veryovkin and M. J. Pellin, *Chem. Mater.*, 2013, **25**, 313–319.
- 95 E. Thimsen, S. C. Riha, S. V. Baryshev, A. B. F. Martinson, J. W. Elam and M. J. Pellin, *Chem. Mater.*, 2012, **24**, 3188–3196.
- 96 P. Yin, L. Sun, X. Han, C. Xia, H. Wu and F. Wang, *Rare Met. Mater. Eng.*, 2016, **45**, 1700–1704.
- 97 S. M. Lee, Y. N. Ko, S. H. Choi, J. H. Kim and Y. C. Kang, *Electrochim. Acta*, 2015, **167**, 287–293.
- 98 R. B. Ettliger, A. Crovetto, S. Canulescu, A. Cazzaniga, L. Ravnkilde, T. Youngman, O. Hansen, N. Pryds and J. Schou, *Appl. Phys. A: Mater. Sci. Process.*, 2016, **122**, 1–10.
- 99 B. Li, L. Jiang, X. Li, P. Ran, P. Zuo, A. Wang, L. Qu, Y. Zhao, Z. Cheng and Y. Lu, *Sci. Rep.*, 2017, **7**, 1–12.
- 100 C. Liang, Y. Shimizu, T. Sasaki, H. Umehara and N. Koshizaki, *J. Phys. Chem. B*, 2004, **108**, 9728–9733.
- 101 X. Huang, M. G. Willinger, H. Fan, Z. L. Xie, L. Wang, A. Klein-Hoffmann, F. Girgsdies, C. S. Lee and X. M. Meng, *Nanoscale*, 2014, **6**, 8787–8795.
- 102 A. D. Mani, N. Xanthopoulos, D. Laub and C. H. Subrahmanyam, *J. Chem. Sci.*, 2014, **126**, 967–973.
- 103 N. M. Hosny and A. Dahshan, *J. Mol. Struct.*, 2015, **1085**, 78–83.
- 104 S. Vaidya, A. Patra and A. K. Ganguli, *Colloids Surf., A*, 2010, **363**, 130–134.
- 105 Z. Zhang, B. Xie, J. Li, B. Fang and Y. Lin, *Colloids Surf., A*, 2018, **546**, 203–211.
- 106 S. V. P. Vattikuti, C. Byon, C. V. Reddy, J. Shim and B. Venkatesh, *Appl. Phys. A: Mater. Sci. Process.*, 2015, **119**, 813–823.
- 107 S. Yadav and P. K. Bajpai, *Nano-Struct. Nano-Objects*, 2017, **10**, 151–158.
- 108 W. Dong, X. Wang, B. Li, L. Wang, B. Chen, C. Li, X. Li, T. Zhang and Z. Shi, *Dalton Trans.*, 2011, **40**, 243–248.
- 109 K. Li, Q. Wang, X. Cheng, T. Lv and T. Ying, *J. Alloys Compd.*, 2010, **504**, L31–L35.
- 110 J. C. Xing, Y. L. Zhu, M. Y. Li and Q. J. Jiao, *Electrochim. Acta*, 2014, **149**, 285–292.
- 111 S. Kamila, B. Mohanty, A. K. Samantara, P. Guha, A. Ghosh, B. Jena, P. V. Satyam, B. K. Mishra and B. K. Jena, *Sci. Rep.*, 2017, **7**, 1–13.
- 112 Y. J. Yuan, D. Chen, J. Zhong, L. X. Yang, J. Wang, M. J. Liu, W. G. Tu, Z. T. Yu and Z. G. Zou, *J. Mater. Chem. A*, 2017, **5**, 15771–15779.
- 113 A. Bhorde, A. Pawbake, P. Sharma, S. Nair, A. Funde, P. Bankar, M. More and S. Jadhkar, *Appl. Phys. A: Mater. Sci. Process.*, 2018, **124**, 1–8.
- 114 C. Bara, A. F. Lamic-Humblot, E. Fonda, A. S. Gay, A. L. Taleb, E. Devers, M. Digne, G. D. Pirngruber and X. Carrier, *J. Catal.*, 2016, **344**, 591–605.
- 115 C. J. Chen and R. K. Chiang, *Dalt. Trans.*, 2011, **40**, 880–885.
- 116 Z. Liu, L. Zhang, R. Wang, S. Poyraz, J. Cook, M. J. Bozack, S. Das, X. Zhang and L. Hu, *Sci. Rep.*, 2016, **6**, 1–8.
- 117 D. H. Youn, J. W. Jang, J. Y. Kim, J. S. Jang, S. H. Choi and J. S. Lee, *Sci. Rep.*, 2014, **4**, 1–8.
- 118 C. W. Raubach, Y. V. B. De Santana, M. M. Ferrer, P. G. C. Buzolin, J. R. Sambrano and E. Longo, *Dalt. Trans.*, 2013, **42**, 11111–11116.
- 119 Y. Li, K. Ye, K. Cheng, J. Yin, D. Cao and G. Wang, *J. Power Sources*, 2015, **274**, 943–950.
- 120 Y. Chen, C. Davoisne, J. M. Tarascon and C. Guéry, *J. Mater. Chem.*, 2012, **22**, 5295–5299.
- 121 X. Rui, H. Tan and Q. Yan, *Nanoscale*, 2014, **6**, 9889–9924.
- 122 X. Jiang, Y. Xie, J. Lu, W. He, L. Zhu and Y. Qian, *J. Mater. Chem.*, 2000, **10**, 2193–2196.

- 123 P. Leidinger, R. Popescu, D. Gerthsen, H. Lünsdorf and C. Feldmann, *Nanoscale*, 2011, **3**, 2544–2551.
- 124 C. Wang, Z. Fang, F. Fan, X. Dong, Y. Peng, S. Hao and L. Long, *CrystEngComm*, 2013, **15**, 5792–5798.
- 125 L. Liu, H. Zhong, Z. Bai, T. Zhang, W. Fu, L. Shi, H. Xie, L. Deng and B. Zou, *Chem. Mater.*, 2013, **25**, 4828–4834.
- 126 Y. Chen, K. Chen, J. Fu, A. Yamaguchi, H. Li, H. Pan, J. Hu, M. Miyachi and M. Liu, *Nano Mater. Sci.*, 2020, **2**, 235–247.
- 127 Y. Liu, Y. Deng, Z. Sun, J. Wei, G. Zheng, A. M. Asiri, S. B. Khan, M. M. Rahman and D. Zhao, *Small*, 2013, **9**, 2702–2708.
- 128 Y. Su, X. Lu, M. Xie, H. Geng, H. Wei, Z. Yang and Y. Zhang, *Nanoscale*, 2013, **5**, 8889–8893.
- 129 J. Liu and D. Xue, *J. Mater. Chem.*, 2011, **21**, 223–228.
- 130 H. Mazor, D. Golodnitsky, L. Burstein and E. Peled, *Electrochem. Solid-State Lett.*, 2009, **12**, A232.
- 131 C. Justin Raj, B. C. Kim, W. J. Cho, W. G. Lee, Y. Seo and K. H. Yu, *J. Alloys Compd.*, 2014, **586**, 191–196.
- 132 K. H. Liu, H. X. Zhong, S. J. Li, Y. X. Duan, M. M. Shi, X. B. Zhang, J. M. Yan and Q. Jiang, *Prog. Mater. Sci.*, 2018, **92**, 64–111.
- 133 A. Hasani, M. Tekalgne, Q. Van Le, H. W. Jang and S. Y. Kim, *J. Mater. Chem. A*, 2019, **7**, 430–454.
- 134 P. Geng, S. Zheng, H. Tang, R. Zhu, L. Zhang, S. Cao, H. Xue and H. Pang, *Adv. Energy Mater.*, 2018, **8**, 1703259.
- 135 Q. Yun, Q. Lu, X. Zhang, C. Tan and H. Zhang, *Angew. Chem., Int. Ed.*, 2018, **57**, 626–646.
- 136 Z. Fu, M. Wu, Y. Zhou, Z. Lyu, Y. Ouyang, Q. Li and J. Wang, *J. Mater. Chem. A*, 2022, **10**, 5699–5716.
- 137 A. W. Kahsay, K. B. Ibrahim, M. C. Tsai, M. K. Birhanu, S. A. Chala, W. N. Su and B. J. Hwang, *Catal. Lett.*, 2019, **149**, 860–869.
- 138 S. Wang, T. Kou, J. B. Varley, S. A. Akhade, S. E. Weitzner, S. E. Baker, E. B. Duoss and Y. Li, *ACS Mater. Lett.*, 2021, **3**, 100–109.
- 139 C. H. M. van Oversteeg, M. Tapia Rosales, K. H. Helfferich, M. Ghiasi, J. D. Meeldijk, N. J. Firet, P. Ngene, C. de Mello Donegá and P. E. de Jongh, *Catal. Today*, 2021, **377**, 157–165.
- 140 B. Zhang, M. Wang, J. Ding, Y. Li, G. Cao, M. T. Bernards, Y. He and Y. Shi, *J. CO<sub>2</sub> Util.*, 2020, **39**, 101169.
- 141 X. Duan, J. Xu, Z. Wei, J. Ma, S. Guo, H. Liu and S. Dou, *Small Methods*, 2017, **1**, 1700156.
- 142 Q. Wang, Y. Lei, Y. Wang, Y. Liu, C. Song, J. Zeng, Y. Song, X. Duan, D. Wang and Y. Li, *Energy Environ. Sci.*, 2020, **13**, 1593–1616.
- 143 D. Voiry, H. S. Shin, K. P. Loh and M. Chhowalla, *Nat. Rev. Chem.*, 2018, **2**, 1–17.
- 144 D. Voiry, J. Yang and M. Chhowalla, *Adv. Mater.*, 2016, **28**, 6197–6206.
- 145 T. Shinagawa, G. O. Larrazábal, A. J. Martín, F. Krumeich and J. Pérez-Ramírez, *ACS Catal.*, 2018, **8**, 837–844.
- 146 J. W. Lim, W. J. Dong, J. Y. Park, D. M. Hong and J. L. Lee, *ACS Appl. Mater. Interfaces*, 2020, **12**, 22891–22900.
- 147 Z. Li, N. H. Attanayake, J. L. Blackburn and E. M. Miller, *Energy Environ. Sci.*, 2021, **14**, 6242–6286.
- 148 T. Heliso Dolla, T. Matthews, N. Wendy Maxakato, P. Ndungu and T. Montini, *J. Electroanal. Chem.*, 2023, **928**, 117049.
- 149 Q. G. Zhu, X. F. Sun, X. C. Kang, J. MA, Q. L. Qian and B. X. Han, *Acta Phys.-Chim. Sin.*, 2016, **32**, 261–266.
- 150 P. Shao, S. Ci, L. Yi, P. Cai, P. Huang, C. Cao and Z. Wen, *ChemElectroChem*, 2017, **4**, 2593–2598.
- 151 Y. Gao, Y. Guo, Y. Zou, W. Liu, Y. Luo, B. Liu and C. Zhao, *ACS Appl. Energy Mater.*, 2023, **6**(3), 1340–1354.
- 152 Z. Zhao, X. Peng, X. Liu, X. Sun, J. Shi, L. Han, G. Li and J. Luo, *J. Mater. Chem. A*, 2017, **5**, 20239–20243.
- 153 J. Chen, Y. Tu, Y. Zou, X. Li and J. Jiang, *Mater. Lett.*, 2021, **284**, 128919.
- 154 T. Dou, Y. Qin, F. Zhang and X. Lei, *ACS Appl. Energy Mater.*, 2021, **4**, 4376–4384.
- 155 X. Zhang, R. Sa, F. Zhou, Y. Rui, R. Liu, Z. Wen and R. Wang, *CCS Chem*, 2021, **3**, 199–207.
- 156 C. He, D. Duan, J. Low, Y. Bai, Y. Jiang, X. Wang, S. Chen, R. Long, L. Song and Y. Xiong, *Nano Res.*, 2021, DOI: [10.1007/s12274-021-3532-7](https://doi.org/10.1007/s12274-021-3532-7).
- 157 K. R. Phillips, Y. Katayama, J. Hwang and Y. Shao-Horn, *J. Phys. Chem. Lett.*, 2018, **9**, 4407–4412.
- 158 Y. Deng, Y. Huang, D. Ren, A. D. Handoko, Z. W. Seh, P. Hirunsit and B. S. Yeo, *ACS Appl. Mater. Interfaces*, 2018, **10**, 28572–28581.
- 159 Y. Huang, Y. Deng, A. D. Handoko, G. K. L. Goh and B. S. Yeo, *ChemSusChem*, 2018, **11**, 320–326.
- 160 W. He, I. Liberman, I. Rozenberg, R. Ifraemov and I. Hod, *Angew. Chem.*, 2020, **132**, 8339–8346.
- 161 J. Li, J. Li, C. Dun, W. Chen, D. Zhang, J. Gu, J. J. Urban and J. W. Ager, *RSC Adv.*, 2021, **11**, 23948–23959.
- 162 L. Lin, N. Miao, Y. Wen, S. Zhang, P. Ghosez, Z. Sun and D. A. Allwood, *ACS Nano*, 2016, **10**, 8929–8937.
- 163 L. Dong, S. Guo, Y. Wang, Q. Zhang, L. Gu, C. Pan and J. Zhang, *J. Mater. Chem. A*, 2019, **7**, 27603–27611.
- 164 C. Wei, W. Wu, H. Li, X. Lin, T. Wu, Y. Zhang, Q. Xu, L. Zhang, Y. Zhu, X. Yang, Z. Liu and Q. Xu, *ACS Appl. Mater. Interfaces*, 2019, **11**, 25264–25270.
- 165 T. T. Zhuang, Z. Q. Liang, A. Seifitokaldani, Y. Li, P. De Luna, T. Burdyny, F. Che, F. Meng, Y. Min, R. Quintero-Bermudez, C. T. Dinh, Y. Pang, M. Zhong, B. Zhang, J. Li, P. N. Chen, X. L. Zheng, H. Liang, W. N. Ge, B. J. Ye, D. Sinton, S. H. Yu and E. H. Sargent, *Nat. Catal.*, 2018, **1**, 421–428.
- 166 C. Peng, G. Luo, J. Zhang, M. Chen, Z. Wang, T. K. Sham, L. Zhang, Y. Li and G. Zheng, *Nat. Commun.*, 2021, **12**, 1–8.
- 167 Y. P. Zhu, C. Guo, Y. Zheng and S. Z. Qiao, *Acc. Chem. Res.*, 2017, **50**, 915–923.
- 168 X. Wang, J. Lv, J. Zhang, X. L. Wang, C. Xue, G. Bian, D. Li, Y. Wang and T. Wu, *Nanoscale*, 2020, **12**, 772–784.
- 169 X. Han, T. Mou, S. Liu, M. Ji, Q. Gao, Q. He, H. Xin and H. Zhu, *Nanoscale Horiz.*, 2022, **7**, 508–514.
- 170 C. He, S. Chen, R. Long, L. Song and Y. Xiong, *Sci. China Chem.*, 2020, **63**, 1721–1726.
- 171 C. F. Wen, M. Zhou, P. F. Liu, Y. Liu, X. Wu, F. Mao, S. Dai, B. Xu, X. L. Wang, Z. Jiang, P. Hu, S. Yang, H. F. Wang and H. G. Yang, *Angew. Chem., Int. Ed.*, 2022, **61**(2), e202111700.

- 172 W. Xue, W. Chang, X. Hu, J. Fan and E. Liu, *Chinese J. Catal.*, 2021, **42**, 152–163.
- 173 P. Tan, A. Zhu, L. Qiao, W. Zeng, H. Cui and J. Pan, *J. Colloid Interface Sci.*, 2019, **533**, 452–462.
- 174 P. Tan, A. Zhu, L. Qiao, W. Zeng, Y. Ma, H. Dong, J. Xie and J. Pan, *Inorg. Chem. Front.*, 2019, **6**, 929–939.
- 175 K. Shen, X. Xue, X. Wang, X. Hu, H. Tian and W. Zheng, *RSC Adv.*, 2017, **7**, 23319–23327.
- 176 H. Rabizadeh, A. Feizbakhsh, H. Ahmad Panahi and E. Kono, *Fuller. Nanotub. Carbon Nanostructures*, 2019, **27**, 788–795, DOI: [10.1080/1536383X.2019.1646251](https://doi.org/10.1080/1536383X.2019.1646251).
- 177 R. Shi, H. F. Ye, F. Liang, Z. Wang, K. Li, Y. Weng, Z. Lin, W. F. Fu, C. M. Che and Y. Chen, *Adv. Mater.*, 2018, **30**, 1705941.
- 178 J. W. Shi, D. Sun, Y. Zou, D. Ma, C. He, X. Ji and C. Niu, *Chem. Eng. J.*, 2019, **364**, 11–19.
- 179 R. Bin Wei, P. Y. Kuang, H. Cheng, Y. B. Chen, J. Y. Long, M. Y. Zhang and Z. Q. Liu, *ACS Sustain. Chem. Eng.*, 2017, **5**, 4249–4257.
- 180 R. Bin Wei, Z. L. Huang, G. H. Gu, Z. Wang, L. Zeng, Y. Chen and Z. Q. Liu, *Appl. Catal. B Environ.*, 2018, **231**, 101–107.
- 181 S. Sarkar and D. Basak, *ACS Appl. Mater. Interfaces*, 2015, **7**, 16322–16329.
- 182 Q. Lu, J. Rosen, Y. Zhou, G. S. Hutchings, Y. C. Kimmel, J. G. Chen and F. Jiao, *Nat. Commun.*, 2014, **51**(5), 1–6.
- 183 Y. Wu, P. Zhai, S. Cao, Z. Li, B. Zhang, Y. Zhang, X. Nie, L. Sun and J. Hou, *Adv. Energy Mater.*, 2020, **10**, 1–11.
- 184 F. Gao, S. Hu, X. Zhang, Y. Zheng, H. Wang, Z. Niu, P. Yang, R. Bao, T. Ma, Z. Dang, Y. Guan, X. Zheng, X. Zheng, J. Zhu, M. Gao and S. Yu, *Angew. Chem.*, 2020, **132**, 8784–8790.
- 185 R. He, A. Zhang, Y. Ding, T. Kong, Q. Xiao, H. Li, Y. Liu and J. Zeng, *Adv. Mater.*, 2018, **30**, 1–7.
- 186 Q. Xu, Y. Liu, H. Jiang, Y. Hu, H. Liu and C. Li, *Adv. Energy Mater.*, 2019, **9**, 1802553.
- 187 M. Shen, L. Zhang, M. Wang, J. Tian, X. Jin, L. Guo, L. Wang and J. Shi, *J. Mater. Chem. A*, 2019, **7**, 1556–1563.
- 188 F. Pan, B. Li, W. Deng, Z. Du, Y. Gang, G. Wang and Y. Li, *Appl. Catal. B Environ.*, 2019, **252**, 240–249.
- 189 T. Hou, N. Luo, Y. T. Cui, J. Lu, L. Li, K. E. MacArthur, M. Heggen, R. Chen, F. Fan, W. Tian, S. Jin and F. Wang, *Appl. Catal. B Environ.*, 2019, **245**, 262–270.
- 190 Y. H. Li, L. Cheng, P. F. Liu, L. Zhang, M. Y. Zu, C. W. Wang, Y. H. Jin, X. M. Cao, H. G. Yang and C. Li, *ChemSusChem*, 2018, **11**, 1421–1425.
- 191 L. Cheng, Y. Li, A. Chen, Y. Zhu and C. Li, *Chem. Commun.*, 2020, **56**, 563–566.
- 192 B. Qin, Y. Li, H. Wang, G. Yang, Y. Cao, H. Yu, Q. Zhang, H. Liang and F. Peng, *Nano Energy*, 2019, **60**, 43–51.
- 193 M. Naguib, M. Kurtoglu, V. Presser, J. Lu, J. Niu, M. Heon, L. Hultman, Y. Gogotsi and M. W. Barsoum, *Adv. Mater.*, 2011, **23**, 4248–4253.
- 194 M. Naguib, O. Mashtalir, J. Carle, V. Presser, J. Lu, L. Hultman, Y. Gogotsi and M. W. Barsoum, *ACS Nano*, 2012, **6**, 1322–1331.
- 195 Z. W. Seh, K. D. Fredrickson, B. Anasori, J. Kibsgaard, A. L. Strickler, M. R. Lukatskaya, Y. Gogotsi, T. F. Jaramillo and A. Vojvodic, *ACS Energy Lett.*, 2016, **1**, 589–594.
- 196 R. Meshkian, M. Dahlgqvist, J. Lu, B. Wickman, J. Halim, J. Thörnberg, Q. Tao, S. Li, S. Intikhab, J. Snyder, M. W. Barsoum, M. Yildizhan, J. Palisaitis, L. Hultman, P. O. Å. Persson and J. Rosen, *Adv. Mater.*, 2018, **30**, 1706409.
- 197 Á. Morales-García, F. Calle-Vallejo and F. Illas, *ACS Catal.*, 2020, **10**, 13487–13503.
- 198 Y. Wang, R. Du, Z. Li, H. Song, Z. Chao, D. Zu, D. Chong, N. Gao and C. Li, *Ceram. Int.*, 2021, **47**, 28321–28327.
- 199 L. Cheng, Y. Wang, Y. Li, Y. Shen, Y. Zhen, Z. Xing, L. Lin, A. Chen, Y. Zhu and C. Li, *ChemCatChem*, 2021, **13**, 1161–1164.
- 200 C. Zhan, F. Dattila, C. Rettenmaier, A. Bergmann, S. Kühl, R. García-Muelas, N. López and B. Roldan Cuenya, *ACS Catal.*, 2021, **11**, 7694–7701.
- 201 V. S. S. Mosali, X. Zhang, Y. Liang, L. Li, G. Puxty, M. D. Horne, A. Brajter-Toth, A. M. Bond and J. Zhang, *ChemSusChem*, 2021, **14**, 2924–2934.
- 202 X. L. Gou, J. Chen and P. W. Shen, *Mater. Chem. Phys.*, 2005, **93**, 557–566.
- 203 L. A. Burton, D. Colombara, R. D. Abellon, F. C. Grozema, L. M. Peter, T. J. Savenije, G. Dennler and A. Walsh, *Chem. Mater.*, 2013, **25**, 4908–4916.
- 204 M. R. Pallavolu, Y. Anil Kumar, G. Mani, R. A. Alshgari, M. Ouladsmame and S. W. Joo, *J. Electroanal. Chem.*, 2021, **899**, 115695.
- 205 C. Zhu, F. Wan, H. Ping, H. Wang, W. Wang and Z. Fu, *J. Power Sources*, 2021, **506**, 230180.
- 206 K. Li, S. Yan, Z. Lin and Y. Shi, *J. Alloys Compd.*, 2016, **681**, 486–491.
- 207 Y. Shan, Y. Li and H. Pang, *Adv. Funct. Mater.*, 2020, **30**, 2001298.
- 208 K. J. Norton, F. Alam and D. J. Lewis, *Appl. Sci.*, 2021, **11**, 2062.
- 209 Y. Li, J. P. Tu, X. H. Huang, H. M. Wu and Y. F. Yuan, *Electrochim. Acta*, 2006, **52**, 1383–1389.
- 210 J. Cai, Z. Li and P. K. Shen, *ACS Appl. Mater. Interfaces*, 2012, **4**, 4093–4098.
- 211 A. M. Tripathi and S. Mitra, *RSC Adv.*, 2014, **4**, 10358–10366.
- 212 K. Aso, A. Hayashi and M. Tatsumisago, *Cryst. Growth Des.*, 2011, **11**, 3900–3904.
- 213 Y. Zhang, J. Lu, S. Shen, H. Xu and Q. Wang, *Chem. Commun.*, 2011, **47**, 5226–5228.
- 214 D. D. Vaughn, O. D. Hentz, S. Chen, D. Wang and R. E. Schaak, *Chem. Commun.*, 2012, **48**, 5608–5610.
- 215 Z. Deng, H. Jiang, Y. Hu, C. Li, Y. Liu and H. Liu, *AIChE J.*, 2018, **64**, 1965–1974.
- 216 J. Wang, J. Liu, H. Xu, S. Ji, J. Wang, Y. Zhou, P. Hodgson and Y. Li, *J. Mater. Chem. A*, 2013, **1**, 1117–1122.
- 217 C. Zhai, N. Du and H. Z. D. Yang, *Chem. Commun.*, 2011, **47**, 1270–1272.
- 218 L. Wang, L. Zhuo, Y. Yu and F. Zhao, *Electrochim. Acta*, 2013, **112**, 439–447.



- 219 Y. Du, Z. Yin, X. Rui, Z. Zeng, X. J. Wu, J. Liu, Y. Zhu, J. Zhu, X. Huang, Q. Yan and H. Zhang, *Nanoscale*, 2013, **5**, 1456–1459.
- 220 J. Ma, D. Lei, L. Mei, X. Duan, Q. Li, T. Wang and W. Zheng, *CrystEngComm*, 2012, **14**, 832–836.
- 221 H. Zhong, G. Yang, H. Song, Q. Liao, H. Cui, P. Shen and C. X. Wang, *J. Phys. Chem. C*, 2012, **116**, 9319–9326.
- 222 J. Zai, K. Wang, Y. Su, X. Qian and J. Chen, *J. Power Sources*, 2011, **196**, 3650–3654.
- 223 J. Zai, X. Qian, K. Wang, C. Yu, L. Tao, Y. Xiao and J. Chen, *CrystEngComm*, 2012, **14**, 1364–1375.
- 224 J. Ma, D. Lei, X. Duan, Q. Li, T. Wang, A. Cao, Y. Mao and W. Zheng, *RSC Adv.*, 2012, **2**, 3615–3617.
- 225 A. A. Tedstone, D. J. Lewis and P. O'Brien, *Chem. Mater.*, 2016, **28**, 1965–1974.
- 226 X. Hong, K. Chan, C. Tsai and J. K. Nørskov, *ACS Catal.*, 2016, **6**, 4428–4437.
- 227 R. He, X. Yuan, P. Shao, T. Duan and W. Zhu, *Small*, 2019, **15**, 1–7.
- 228 A. Zhang, R. He, H. Li, Y. Chen, T. Kong, K. Li, H. Ju, J. Zhu, W. Zhu and J. Zeng, *Angew. Chem.*, 2018, **130**, 11120–11124.
- 229 X. Zheng, P. De Luna, F. P. Garcia de Arquer, B. Zhang, N. Becknell, M. B. Ross, Y. Li, M. N. Banis, Y. Li, M. Liu, O. Voznyy, C. T. Dinh, T. Zhuang, P. Stadler, Y. Cui, X. Du, P. Yang and E. H. Sargent, *Joule*, 2017, **1**, 794–805.
- 230 Z. Chen, X. Zhang, M. Jiao, K. Mou, X. Zhang and L. Liu, *Adv. Energy Mater.*, 2020, **10**, 1–8.
- 231 F. Li, L. Chen, M. Xue, T. Williams, Y. Zhang, D. R. MacFarlane and J. Zhang, *Nano Energy*, 2017, **31**, 270–277.
- 232 J. He, X. Liu, H. Liu, Z. Zhao, Y. Ding and J. Luo, *J. Catal.*, 2018, **364**, 125–130.
- 233 H. Cheng, S. Liu, J. Zhang, T. Zhou, N. Zhang, X. S. Zheng, W. Chu, Z. Hu, C. Wu and Y. Xie, *Nano Lett.*, 2020, **20**, 6097–6103.
- 234 J. Xu, S. Lai, M. Hu, S. Ge, R. Xie, F. Li, D. Hua, H. Xu, H. Zhou, R. Wu, J. Fu, Y. Qiu, J. He, C. Li, H. Liu, Y. Liu, J. Sun, X. Liu and J. Luo, *Small Methods*, 2020, **4**, 1–8.
- 235 R. Sakthivel, S. Kubendhiran and S. M. Chen, *Ultrason. Sonochem.*, 2019, **54**, 68–78.
- 236 R. He, X. Qian, J. Yin and Z. Zhu, *J. Cryst. Growth*, 2003, **252**, 505–510.
- 237 P. Kumar Panigrahi and A. Pathak, *J. Nanopart.*, 2013, **2013**, 11.
- 238 D. B. Li, L. Hu, Y. Xie, G. Niu, T. Liu, Y. Zhou, L. Gao, B. Yang and J. Tang, *ACS Photonics*, 2016, **3**, 2122–2128.
- 239 W. Sun, X. Rui, D. Zhang, Y. Jiang, Z. Sun, H. Liu and S. Dou, *J. Power Sources*, 2016, **309**, 135–140.
- 240 S. S. Raut, J. A. Dhobale and B. R. Sankapal, *Phys. E*, 2017, **87**, 209–212.
- 241 D. Guo, C. Hu and C. Zhang, *Mater. Res. Bull.*, 2013, **48**, 1984–1988.
- 242 S. Sadhasivam, N. Anbarasan, M. Mukilan, P. Manivel and K. Jeganathan, *Int. J. Hydrogen Energy*, 2020, **45**, 30080–30090.
- 243 T. O. Ajiboye and D. C. Onwudiwe, *Results Chem.*, 2021, **3**, 100151.
- 244 S. Q. Liu, M. R. Gao, R. F. Feng, L. Gong, H. Zeng and J. L. Luo, *ACS Catal.*, 2021, **11**, 7604–7612.
- 245 Y. Zhang, F. Li, X. Zhang, T. Williams, C. D. Easton, A. M. Bond and J. Zhang, *J. Mater. Chem. A*, 2018, **6**, 4714–4720.
- 246 X. Yang, P. Deng, D. Liu, S. Zhao, D. Li, H. Wu, Y. Ma, B. Y. Xia, M. Li, C. Xiao and S. Ding, *J. Mater. Chem. A*, 2020, **8**, 2472–2480.
- 247 X. Shao and Y. Liu, *J. Electrochem. Soc.*, 2022, **169**, 026505.
- 248 C. Yang, J. Chai, Z. Wang, Y. Xing, J. Peng and Q. Yan, *Chem. Res. Chin. Univ.*, 2020, **36**, 410–419.
- 249 J. Wang, J. Mao, X. Zheng, Y. Zhou and Q. Xu, *Appl. Surf. Sci.*, 2021, **562**, 150197.
- 250 Y. Wang, X. Zhu and Y. Li, *J. Phys. Chem. Lett.*, 2019, **10**, 4663–4667.
- 251 X. Zou and Y. Zhang, *Chem. Soc. Rev.*, 2015, **44**, 5148–5180.
- 252 B. Hinnemann, P. G. Moses, J. Bonde, K. P. Jørgensen, J. H. Nielsen, S. Horch, I. Chorkendorff and J. K. Nørskov, *J. Am. Chem. Soc.*, 2005, **127**, 5308–5309.
- 253 T. F. Jaramillo, K. P. Jørgensen, J. Bonde, J. H. Nielsen, S. Horch and I. Chorkendorff, *Science*, 2007, **317**, 100–102.
- 254 W. Hua, H. H. Sun, F. Xu and J. G. Wang, *Rare Met.*, 2020, **39**, 335–351.
- 255 F. Qi, P. Li, Y. Chen, B. Zheng, X. Liu, F. Lan, Z. Lai, Y. Xu, J. Liu, J. Zhou, J. He and W. Zhang, *Vacuum*, 2015, **119**, 204–208.
- 256 M. Asadi, B. Kumar, A. Behranginia, B. A. Rosen, A. Baskin, N. Reppin, D. Pisasale, P. Phillips, W. Zhu, R. Haasch, R. F. Klie, P. Král, J. Abiade and A. Salehi-Khojin, *Nat. Commun.*, 2014, **5**, 1–8.
- 257 R. Tian, W. Wang, Y. Huang, H. Duan, Y. Guo, H. Kang, H. Li and H. Liu, *J. Mater. Chem. A*, 2016, **4**, 13148–13154.
- 258 L. Ma, G. Huang, W. Chen, Z. Wang, J. Ye, H. Li, D. Chen and J. Y. Lee, *J. Power Sources*, 2014, **264**, 262–271.
- 259 Y. Shi, Y. Wang, J. I. Wong, A. Y. S. Tan, C. L. Hsu, L. J. Li, Y. C. Lu and H. Y. Yang, *Sci. Rep.*, 2013, **3**, 1–8.
- 260 Q. Wang and J. Li, *J. Phys. Chem. C*, 2007, **111**, 1675–1682.
- 261 C. Wang, W. Wan, Y. Huang, J. Chen, H. H. Zhou and X. X. Zhang, *Nanoscale*, 2014, **6**, 5351–5358.
- 262 L. Fei, Y. Xu, X. Wu, G. Chen, Y. Li, B. Li, S. Deng, S. Smirnov, H. Fan and H. Luo, *Nanoscale*, 2014, **6**, 3664–3669.
- 263 F. Li, S. F. Zhao, L. Chen, A. Khan, D. R. MacFarlane and J. Zhang, *Energy Environ. Sci.*, 2016, **9**, 216–223.
- 264 K. Lv, W. Suo, M. Shao, Y. Zhu, X. Wang, J. Feng and M. Fang, *Nano Energy*, 2019, **63**, 103834.
- 265 N. Hussain, M. A. Abdelkareem, H. Alawadhi, K. Elsaid and A. G. Olabi, *Chem. Eng. Sci.*, 2022, **258**, 117757.
- 266 H. Li, X. Liu, S. Chen, D. Yang, Q. Zhang, L. Song, H. Xiao, Q. Zhang, L. Gu and X. Wang, *Adv. Energy Mater.*, 2019, **9**, 1–11.
- 267 G. Shi, L. Yu, X. Ba, X. Zhang, J. Zhou and Y. Yu, *Dalt. Trans.*, 2017, **46**, 10569–10577.
- 268 P. Abbasi, M. Asadi, C. Liu, S. Sharifi-Asl, B. Sayahpour, A. Behranginia, P. Zapol, R. Shahbazian-Yassar, L. A. Curtiss and A. Salehi-Khojin, *ACS Nano*, 2017, **11**, 453–460.

- 269 N. Hussain, M. A. Abdelkareem, H. Alawadhi, A. H. Alami and K. Elsaid, *Appl. Phys. A: Mater. Sci. Process.*, 2022, **128**, 15–20.
- 270 K. Lv, C. Teng, M. Shi, Y. Yuan, Y. Zhu, J. Wang, Z. Kong, X. Lu and Y. Zhu, *Adv. Funct. Mater.*, 2018, **28**, 1–10.
- 271 Z. W. Chen, W. Gao, W. T. Zheng and Q. Jiang, *ChemSusChem*, 2018, **11**, 1455–1459.
- 272 S. Kang, S. Han and Y. Kang, *ChemSusChem*, 2019, **12**, 2671–2678.
- 273 Q. Gong, L. Cheng, C. Liu, M. Zhang, Q. Feng, H. Ye, M. Zeng, L. Xie, Z. Liu and Y. Li, *ACS Catal.*, 2015, **5**, 2213–2219.
- 274 C. Xu, S. Peng, C. Tan, H. Ang, H. Tan, H. Zhang and Q. Yan, *J. Mater. Chem. A*, 2014, **2**, 5597–5601.
- 275 V. Kiran, D. Mukherjee, R. N. Jenjeti and S. Sampath, *Nanoscale*, 2014, **6**, 12856–12863.
- 276 J. Xu, X. Li, W. Liu, Y. Sun, Z. Ju, T. Yao, C. Wang, H. Ju, J. Zhu, S. Wei and Y. Xie, *Angew. Chem., Int. Ed.*, 2017, **56**, 9121–9125.
- 277 K. Chan, C. Tsai, H. A. Hansen and J. K. Nørskov, *ChemCatChem*, 2014, **6**, 1899–1905.
- 278 P. Pistor, J. M. M. Álvarez, M. León, M. Di Michiel, S. Schorr, R. Klenk and S. Lehmann, *Acta Crystallogr., Sect. B: Struct. Sci., Cryst. Eng. Mater.*, 2016, **72**, 410–415.
- 279 Y. Liu, H. Xu and Y. Qian, *Cryst. Growth Des.*, 2006, **6**, 1304–1307.
- 280 F. Ye, C. Wang, G. Du, X. Chen, Y. Zhong and J. Z. Jiang, *J. Mater. Chem.*, 2011, **21**, 17063–17065.
- 281 G. Li and H. Liu, *J. Mater. Chem.*, 2011, **21**, 18398–18402.
- 282 X. Yuan, Y. Luo, B. Zhang, C. Dong, J. Lei, F. Yi, T. Duan, W. Zhu and R. He, *Chem. Commun.*, 2020, **56**, 4212–4215.
- 283 A. Zhang, Y. Liang, H. Li, X. Zhao, Y. Chen, B. Zhang, W. Zhu and J. Zeng, *Nano Lett.*, 2019, **19**, 6547–6553.
- 284 L. P. Chi, Z. Z. Niu, X. L. Zhang, P. P. Yang, J. Liao, F. Y. Gao, Z. Z. Wu, K. Bin Tang and M. R. Gao, *Nat. Commun.*, 2021, **12**, 1–9.
- 285 J. Feng, H. Gao, J. Feng, L. Liu, S. Zeng, H. Dong, Y. Bai, L. Liu and X. Zhang, *ChemCatChem*, 2020, **12**, 926–931.
- 286 W. Ma, S. Xie, X. G. Zhang, F. Sun, J. Kang, Z. Jiang, Q. Zhang, D. Y. Wu and Y. Wang, *Nat. Commun.*, 2019, **10**, 892–901.
- 287 C. H. Lee and M. W. Kanan, *ACS Catal.*, 2015, **5**, 465–469.
- 288 J. E. Pander, J. W. J. Lum and B. S. Yeo, *J. Mater. Chem. A*, 2019, **7**, 4093–4101.
- 289 Z. Zhang, C. Liu, J. T. Brosnahan, H. Zhou, W. Xu and S. Zhang, *J. Mater. Chem. A*, 2019, **7**, 23775–23780.
- 290 X. Fang, T. Zhai, U. K. Gautam, L. Li, L. Wu, Y. Bando and D. Golberg, *Prog. Mater. Sci.*, 2011, **56**, 175–287.
- 291 Y.-C. Wang, I.-C. Leu, M.-H. Hon, Y. Xu, H. Wu, Y. Cai, X.-J. Xu, G.-T. Fei, W.-H. Yu, X.-W. Wang, L. Chen and L.-D. Zhang, *Nanotechnology*, 2005, **17**, 426.
- 292 G. H. Yue, P. X. Yan, D. Yan, X. Y. Fan, M. X. Wang, D. M. Qu and J. Z. Liu, *Appl. Phys. A*, 2006, **84**, 409–412.
- 293 X. Chen, H. Xu, N. Xu, F. Zhao, W. Lin, G. Lin, Y. Fu, Z. Huang, H. Wang and M. Wu, *Inorg. Chem.*, 2003, **42**, 3100–3106.
- 294 S.-H. Yu and M. Yoshimura, *Adv. Mater.*, 2002, **14**(4), 296–300.
- 295 Y. C. Zhu, Y. Bando and Y. Uemura, *Chem. Commun.*, 2003, **3**, 836–837.
- 296 S. Liang, X. Yeming and L. Quan, *Cryst. Growth Des.*, 2009, **9**, 2214–2219.
- 297 J. Z. Zhen, J. X. Liu, T. Y. Chen, F. Shi, Y. N. Dai, B. Yang, Y. F. Li, X. Wang, T. G. Nong, Y. Q. Hu and J. Shi, *J. Alloys Compd.*, 2019, **771**, 994–999.
- 298 C. Li, G. Shen, R. Zhang, D. Wu, C. Zou, T. Ling, H. Liu, C. Dong and X. W. Du, *J. Mater. Chem. A*, 2019, **7**, 1418–1423.
- 299 Y. Song, Y. Wang, J. Shao, K. Ye, Q. Wang and G. Wang, *ACS Appl. Mater. Interfaces*, 2022, **14**(18), 20368–20374.
- 300 V. V. Ivanovskaya and G. Seifert, *Solid State Commun.*, 2004, **130**, 175–180.
- 301 M. Inoue and H. Negishi, *J. Phys. Chem.*, 1986, **90**, 235–238.
- 302 A. Aljabour, H. Coskun, X. Zheng, M. G. Kibria, M. Strobel, S. Hild, M. Kehrler, D. Stifter, E. H. Sargent and P. Stadler, *ACS Catal.*, 2020, **10**, 66–72.
- 303 C. Simon, J. Zander, T. Kottakkat, M. Weiss, J. Timm, C. Roth and R. Marschall, *ACS Appl. Energy Mater.*, 2021, **4**, 8702–8708.
- 304 S. Zhao, S. Guo, C. Zhu, J. Gao, H. Li, H. Huang, Y. Liu and Z. Kang, *RSC Adv.*, 2017, **7**, 1376–1381.
- 305 S. Piontek, K. Junge Puring, D. Siegmund, M. Smialkowski, I. Sinev, D. Tetzlaff, B. Roldan Cuenya and U. P. Apfel, *Chem. Sci.*, 2019, **10**, 1075–1081.
- 306 D. Tetzlaff, K. Pellumbi, K. Junge Puring, D. Siegmund, W. S. K. Polet, M. P. Checinski and U. P. Apfel, *ChemElectroChem*, 2021, **8**, 3161–3167.
- 307 K. Pellumbi, M. Smialkowski, D. Siegmund and U. P. Apfel, *Chem.–Eur. J.*, 2020, **26**, 9938–9944.
- 308 Z. Ma, T. Wan, D. Zhang, J. A. Yuwono, C. Tsounis, J. Jiang, Y.-H. Chou, X. Lu, P. V. Kumar, Y. H. Ng, D. Chu, C. Y. Toe, Z. Han and R. Amal, *ACS Nano*, 2023, **17**(3), 2387–2398.
- 309 D. Liu, Y. Liu and M. Li, *ACS Appl. Mater. Interfaces*, 2020, **12**(11), 6145–6153.
- 310 T. Cheng, H. Xiao and W. A. Goddard, *J. Am. Chem. Soc.*, 2016, **138**, 13802–13805.
- 311 X. Han, Q. Wang, Y. Wu and C. Wu, *Electrochim. Acta*, 2022, **402**, 139526.
- 312 P. Lu, X. Tan, H. Zhao, Q. Xiang, K. Liu, X. Zhao, X. Yin, X. Li, X. Hai, S. Xi, A. T. S. Wee, S. J. Pennycook, X. Yu, M. Yuan, J. Wu, G. Zhang, S. C. Smith and Z. Yin, *ACS Nano*, 2021, **15**, 5671–5678.
- 313 H. Yang, Y. Wu, G. Li, Q. Lin, Q. Hu, Q. Zhang, J. Liu and C. He, *J. Am. Chem. Soc.*, 2019, **141**, 12717–12723.
- 314 K. Lakshmanan, W. H. Huang, S. A. Chala, B. W. Taklu, E. A. Moges, J. F. Lee, P. Y. Huang, Y. C. Lee, M. C. Tsai, W. N. Su and B. J. Hwang, *Adv. Funct. Mater.*, 2022, **32**, 2109310.
- 315 L. Han, S. Song, M. Liu, S. Yao, Z. Liang, H. Cheng, Z. Ren, W. Liu, R. Lin, G. Qi, X. Liu, Q. Wu, J. Luo, H. L. Xin, X. Liu, Q. Wu, J. Luo and H. L. Xin, *J. Am. Chem. Soc.*, 2020, **142**, 12563–12567.

- 316 A. Guan, Z. Chen, Y. Quan, C. Peng, Z. Wang, T. K. Sham, C. Yang, Y. Ji, L. Qian, X. Xu and G. Zheng, *ACS Energy Lett.*, 2020, **5**, 1044–1053.
- 317 G. Qu, K. Wei, K. Pan, J. Qin, J. Lv, J. Li and P. Ning, *Nanoscale*, 2023, **15**, 3666–3692.
- 318 Z. Wang, C. Wang, Y. Hu, S. Yang, J. Yang, W. Chen, H. Zhou, F. Zhou, L. Wang, J. Du, Y. Li and Y. Wu, *Nano Res.*, 2021, **14**, 2790–2796.
- 319 J. Guo, W. Zhang, L. H. Zhang, D. Chen, J. Zhan, X. Wang, N. R. Shiju and F. Yu, *Adv. Sci.*, 2021, **8**, 2102884.
- 320 Y.-N. Gong, L. Jiao, Y. Qian, C.-Y. Pan, L. Zheng, X. Cai, B. Liu, S.-H. Yu and H.-L. Jiang, *Angew. Chem.*, 2020, **132**, 2727–2731.
- 321 S. Liu, M. Jin, J. Sun, Y. Qin, S. Gao, Y. Chen, S. Zhang, J. Luo and X. Liu, *Chem. Eng. J.*, 2022, **437**, 135294.
- 322 B. Chen, B. Li, Z. Tian, W. Liu, W. P. Liu, W. Sun, K. Wang, L. Chen and J. Jiang, *Adv. Energy Mater.*, 2021, **11**, 2102152.
- 323 H. Chang, H. Pan, F. Wang, Z. Zhang, Y. Kang and S. Min, *Nanoscale*, 2022, **14**, 10003–10008.
- 324 W. Hua, H. Sun, L. Lin, Q. Mu, B. Yang, Y. Su, H. Wu, F. Lyu, J. Zhong, Z. Deng and Y. Peng, *Chem. Eng. J.*, 2022, **446**, 137296.
- 325 H. Li, Y. Pan, Z. Wang, Y. Yu, J. Xiong, H. Du, J. Lai, L. Wang and S. Feng, *Nano Res.*, 2022, **15**, 3056–3064.
- 326 X. Sheng, W. Ge, H. Jiang and C. Li, *Adv. Mater.*, 2022, **34**, 2201295.
- 327 G. Hwa Jeong, Y. Chuan Tan, J. Tae Song, G. Y. Lee, H. Jin Lee, J. Lim, H. Young Jeong, S. Won, J. Oh and S. Ouk Kim, *Chem. Eng. J.*, 2021, **426**, 131063.
- 328 J. Feng, L. Zheng, C. Jiang, Z. Chen, L. Liu, S. Zeng, L. Bai, S. Zhang and X. Zhang, *Green Chem.*, 2021, **23**, 5461–5466.
- 329 S. A. Abbas, J. T. Song, Y. C. Tan, K. M. Nam, J. Oh and K. D. Jung, *ACS Appl. Energy Mater.*, 2020, **3**, 8739–8745.
- 330 H. Yang, P. Zhang, X. Yi, C. Yan, D. Pang, L. Chen, S. B. Wang, C. Wang, B. Liu, G. Zhang, Z. Zhou and X. Li, *Chem. Eng. J.*, 2022, **440**, 135749.
- 331 T. Ding, X. Liu, Z. Tao, T. Liu, T. Chen, W. Zhang, X. Shen, D. Liu, S. Wang, B. Pang, D. Wu, L. Cao, L. Wang, T. Liu, Y. Li, H. Sheng, M. Zhu and T. Yao, *J. Am. Chem. Soc.*, 2021, **143**, 11317–11324.
- 332 C. Wang, Y. Liu, H. Ren, Q. Guan, S. Chou and W. Li, *ACS Catal.*, 2022, **12**, 2513–2521.
- 333 K. Jiang, R. B. Sandberg, A. J. Akey, X. Liu, D. C. Bell, J. K. Nørskov, K. Chan and H. Wang, *Nat. Catal.*, 2018, **1**, 111–119.
- 334 M. Zheng, P. Wang, X. Zhi, K. Yang, Y. Jiao, J. Duan, Y. Zheng and S. Z. Qiao, *J. Am. Chem. Soc.*, 2022, **144**, 14936–14944.
- 335 Z. Gu, H. Shen, Z. Chen, Y. Yang, C. Yang, Y. Ji, Y. Wang, C. Zhu, J. Liu, J. Li, T. K. Sham, X. Xu and G. Zheng, *Joule*, 2021, **5**, 429–440.
- 336 H. Li, T. Liu, P. Wei, L. Lin, D. Gao, G. Wang and X. Bao, *Angew. Chem.*, 2021, **133**, 14450–14454.
- 337 D. Zhong, Z. J. Zhao, Q. Zhao, D. Cheng, B. Liu, G. Zhang, W. Deng, H. Dong, L. Zhang, J. Li, J. Li and J. Gong, *Angew. Chem., Int. Ed.*, 2021, **60**, 4879–4885.
- 338 Y. Wang, Z. Wang, C. T. Dinh, J. Li, A. Ozden, M. Golam Kibria, A. Seifitokaldani, C. S. Tan, C. M. Gabardo, M. Luo, H. Zhou, F. Li, Y. Lum, C. McCallum, Y. Xu, M. Liu, A. Proppe, A. Johnston, P. Todorovic, T. T. Zhuang, D. Sinton, S. O. Kelley and E. H. Sargent, *Nat. Catal.*, 2019, **32**(3), 98–106.
- 339 H. Xu, D. Rebollar, H. He, L. Chong, Y. Liu, C. Liu, C. J. Sun, T. Li, J. V. Muntean, R. E. Winans, D. J. Liu and T. Xu, *Nat. Energy*, 2020, **58**(5), 623–632.
- 340 C. Choi, S. Kwon, T. Cheng, M. Xu, P. Tieu, C. Lee, J. Cai, H. M. Lee, X. Pan, X. Duan, W. A. Goddard and Y. Huang, *Nat. Catal.*, 2020, **310**(3), 804–812.
- 341 C. Choi, T. Cheng, M. F. Espinosa, H. Fei, X. Duan, W. A. Goddard and Y. Huang, *Adv. Mater.*, 2019, **31**, 1805405.
- 342 B. Zhang, J. Zhang, M. Hua, Q. Wan, Z. Su, X. Tan, L. Liu, F. Zhang, G. Chen, D. Tan, X. Cheng, B. Han, L. Zheng and G. Mo, *J. Am. Chem. Soc.*, 2020, **142**, 13606–13613.
- 343 M. Zhong, K. Tran, Y. Min, C. Wang, Z. Wang, C. T. Dinh, P. De Luna, Z. Yu, A. S. Rasouli, P. Brodersen, S. Sun, O. Voznyy, C. S. Tan, M. Askerka, F. Che, M. Liu, A. Seifitokaldani, Y. Pang, S. C. Lo, A. Ip, Z. Ulissi and E. H. Sargent, *Nature*, 2020, **581**, 178–183.
- 344 S. Mou, Y. Li, L. Yue, J. Liang, Y. Luo, Q. Liu, T. Li, S. Lu, A. M. Asiri, X. Xiong, D. Ma and X. Sun, *Nano Res.*, 2021, **14**, 2831–2836.
- 345 J. Zhu, M. Xiao, D. Ren, R. Gao, X. Liu, Z. Zhang, D. Luo, W. Xing, D. Su, A. Yu and Z. Chen, *J. Am. Chem. Soc.*, 2022, **144**, 9661–9671.
- 346 Q. Zhao, C. Zhang, R. Hu, Z. Du, J. Gu, Y. Cui, X. Chen, W. Xu, Z. Cheng, S. Li, B. Li, Y. Liu, W. Chen, C. Liu, J. Shang, L. Song and S. Yang, *ACS Nano*, 2021, **15**, 4927–4936.
- 347 D. Yang, Q. Zhu, C. Chen, H. Liu, Z. Liu, Z. Zhao, X. Zhang, S. Liu and B. Han, *Nat. Commun.*, 2019, **10**(10), 1–9.
- 348 M. K. Kim, H. J. Kim, H. Lim, Y. Kwon and H. M. Jeong, *Electrochim. Acta*, 2019, **306**, 28–34.
- 349 S. Chen, B. Wang, J. Zhu, L. Wang, H. Ou, Z. Zhang, X. Liang, L. Zheng, L. Zhou, Y. Q. Su, D. Wang and Y. Li, *Nano Lett.*, 2021, **21**, 7325–7331.
- 350 A. B. Laursen, K. U. D. Calvinho, T. A. Goetjen, K. M. K. Yap, S. Hwang, H. Yang, E. Garfunkel and G. C. Dismukes, *Electrochim. Acta*, 2021, **391**, 138889.
- 351 B. Wei, Y. Xiong, Z. Zhang, J. Hao, L. Li and W. Shi, *Appl. Catal. B Environ.*, 2021, **283**, 119646.