Electronic Supporting Information for

Selective CO_2 reduction towards a single upgraded product: a Minireview on multi-elemental copper-free electrocatalysts

Madeleine K. Wilsey,[a] Connor P. Cox,[a] Ryland C. Forsythe,[b] Luke R. McCarney[b] and Astrid M. Müller*[a,b]

a. Materials Science Program, University of Rochester, Rochester, New York 14627, United States.
b. Department of Chemical Engineering, University of Rochester, Rochester, New York 14627, United States.
*Corresponding author. E-mail: astrid.mueller@rochester.edu

Table S1: Tabulated summary of metal-containing multi-elemental copper-free CO_2 reduction electrocatalysts. Abbreviations: bmim, 1-butyl-3-methylimidazolium; CNF, carbon nanofibres; EMIM, 1-ethyl-3-methylimidazolium; Fc, ferrocene; FE, faradaic efficiency; FTO, fluorine-doped tin oxide; MeCN, acetonitrile; ML, monolayer; NGO, nitrogenated graphene oxide; NHE, normal hydrogen electrode; NPs, nanoparticles; Pc, phthalocyanine; RHE, reversible hydrogen electrode; SCE, saturated calomel electrode; YLS–29BC, conductive carbon paper used for gas diffusion layer (no explanation given for abbreviation). Symbols: (Cl,N):Mn, chlorine and nitrogen-doped manganese.

Elemental composition	Material	Morphology or size	Supporting electrode	Electrolyte (conditions)	Potential at reported current density	Reported current density (mA cm^{-2})	FE (product)	Ref.
Vanadium								
V– In_2O_3	V-doped In_2O_3	–	Glassy carbon electrode	Aqueous 0.1 M $KHCO_3$ at pH 6.8 (saturated with CO_2)	–0.83 V vs. RHE	–2.5	30% (H_2) 30% (HCOOH) 25% (CO) 15.8% (CH_3OH)	1
Chromium								
Cr–N–C	Cr–N–C	–	Carbon paper	Aqueous 0.1 M $KHCO_3$ at pH 6.8 (saturated with CO_2)	–0.7 V vs. RHE	–0.5	75% (CO) 25% (H_2)	2
Molybdenum								
Mo–Ag	Mo–Ag	Nanosheets	Carbon paper	0.5 M [bmim]BF_4/MeCN (saturated with CO_2)	–0.7 V vs. RHE	–7.0	48% (CH_3OH) 22% (CH_4) 18% (CO) 12% (H_2)	3
Mo–P	MoP	–	Indium-doped porous carbon	30 wt% [bmim]PF_6, 65 wt% MeCN, and 5 wt % H_2O	–2.2 V vs. Ag/AgCl	–43.8	96.5% (HCOOH) 3.5% (CO and H_2)	4
Mo–Se–S	MoSeS alloy	Monolayers	Glassy carbon electrode	4 mol% / 96 mol% EMIM–BF_4 / H_2O at pH 4 (saturated with CO_2)	–1.15 V vs. RHE	–43	54.8% (H_2) 45.2% (CO)	5
Mo–S	Layered MoS_2	Vertically aligned nanoflakes	Glassy carbon electrode	96 mol% water / 4 mol% EMIM–BF_4 at pH 4 (saturated with CO_2)	–0.76 V vs. RHE	–65	98% (CO) 2% (H_2)	6
Mo–Bi	Mo–Bi	Nanosheets	Carbon paper	0.5 M [bmim]BF_4 / MeCN (saturated with CO_2)	–0.7 V vs. RHE	–12.1	71.2% (CH_3OH) 10% (CO) 10% (H_2) 8% (CH_4)	3

Elemental composition	Material	Morphology or size	Supporting electrode	Electrolyte (conditions)	Potential at reported current density	Reported current density (mA cm^{-2})	FE (product)	Ref.
Mo–Au	Mo-doped Au NPs	8.2 ± 0.2 nm	Carbon black	Aqueous 0.5 M $KHCO_3$ (saturated with CO_2)	−0.4 V vs. RHE	−11.22	97.5% (CO)	7
Mo–Pb	MoO_2 on Pb	–	Lead electrode	Aqueous 0.3 M [bmim]PF_6	−2.3 V vs. Fc/Fc^+	–	60.9% ($HCOO^-$) 21.8% (CO) 8.2% (C_2O_4)	8
Tungsten								
W–Au	Au overlayer on W	Near surface alloy	Tungsten	Aqueous 0.1 M $KHCO_3$ (saturated with CO_2)	−1.8 V vs. Ag/AgCl	−0.052	0.5% (CH_3OH)	9
W–Se	WSe_2	Nanoflakes	Glassy carbon electrode	50 vol% / 50 vol% EMIM–BF_4 / H_2O at pH 3.2	−0.164 V vs. RHE	−18.95	76% (H_2) 24% (CO)	10
Manganese								
Mn–N–C	Mn–N–C	–	Carbon paper	Aqueous 0.1 M $KHCO_3$ at pH 6.8 (saturated with CO_2)	−0.6 V vs. RHE	−0.5	70% (CO) 30% (H_2)	2
(Cl,N):Mn	(Cl,N):Mn on graphene	Single Mn atoms on graphene	Carbon paper	Aqueous 0.5 M $KHCO_3$ buffer (saturated with CO_2)	−0.6 V vs. RHE	−13.4	97% (CO)	11
(Br, N):Mn	(Br, N):Mn on graphene	Single Mn atoms on graphene	Carbon paper	Aqueous 0.5 M $KHCO_3$ buffer (saturated with CO_2)	−0.6 V vs. RHE	–	92% (CO)	11
(I, N):Mn	(I, N):Mn on graphene	Single Mn atoms on graphene	Carbon paper	Aqueous 0.5 M $KHCO_3$ buffer (saturated with CO_2)	−0.5 V vs. RHE	–	89% (CO)	11
Iron								
FeMn–N–C	FeMn-N-C	–	Glassy carbon electrode	Aqueous 0.1 M $KHCO_3$ at pH 6.8 (saturated with CO_2)	−0.50 V vs. RHE	−1.8	80% (CO)	12
Fe–N–C	Fe–N–C	–	Porous carbon paper	Aqueous 0.5 M $NaHCO_3$ buffer (saturated with CO_2)	−0.5 V vs. RHE	−6.0	90% (CO)	13
	Fe–N–C	10 nm Mesopore diameter	Glassy carbon electrode	Aqueous 0.5 M $KHCO_3$ buffer	−0.47 V vs. RHE	−1.5	85% (CO) 15% (H_2)	14
FeS_2–NiS	FeS_2–NiS nanocomposite	Homogenous nanocompo-site with 14 nm NPs	Carbon fibre paper	Aqueous 0.5 M $KHCO_3$ buffer at pH 7.5 (saturated with CO_2)	−0.6 V vs. RHE	−7.8	64% (CH_3OH) 19% (unspecified) 17% (H_2)	15

Elemental composition	Material	Morphology or size	Supporting electrode	Electrolyte (conditions)	Potential at reported current density	Reported current density (mA cm^{-2})	FE (product)	Ref.
Fe–P	FeP nanoarray	–	Titanium mesh	Aqueous 0.5 M $KHCO_3$ (saturated with CO_2)	–0.2 V vs. RHE	–	80.2% (CH_3OH) 14.1% (C_2H_5OH) 5.7% (H_2)	16
Fe–P–S	$Fe_2P_2S_6$	1.3 nm thick nanosheet	Carbon paper	Aqueous 0.5 M $KHCO_3$ (saturated with CO_2)	–0.2 V vs. RHE	–	65.2% (CH_3OH) 23.1% (CH_3CH_2OH) 11.7% (H_2)	17
Fe–Ni–S–Se	$Fe_{4.5}Ni_{4.5}S_4Se_4$	–	Polished pellet electrodes encapsulated in a Teflon housing	Acetonitrile (saturated with CO_2, 24 ppm water)	–3.2 V vs. NHE	–100	95.3% (CO) 4.7% (H_2)	18
Ruthenium								
Ru–Pd	Ru:Pd (1:1) alloy	–	Metal loaded gas diffusion electrode	Aqueous 0.5 M $KHCO_3$ (saturated with CO_2, gas diffusion cell)	–1.1 V vs. NHE	–80	90% (HCOOH) 10% (H_2)	19
Cobalt								
Co–Pc	Co centre with Pc ligand	–	Carbon paper	Aqueous 0.1 M $KHCO_3$ at pH 6.8 (saturated with CO_2)	–0.8 V vs. RHE	–4.0	99% (CO) 1% (H_2)	20
Co–N–C	(Co, N):C	Cobalt and nitrogen-doped carbon matrix	Glassy carbon electrode	Aqueous 0.5 M $KHCO_3$ buffer	–0.57 V vs. RHE	–5.6	86% (H_2) 14% (CO)	14
N–P–Co	(N, P, Co):C	Uniformly dispersed N, P, and Co on porous Carbon framework	Carbon paper	Aqueous 0.1 M $KHCO_3$ buffer at pH 6.8 (saturated with CO_2)	–0.59 V vs. RHE	–3.1	62% (CO) 38% (H_2)	21
Co–Fe	CoO_x nanoclusters on graphene supported FePc	–	Carbon paper with gas diffusion layer	Aqueous 0.5 M $KHCO_3$ buffer (saturated with CO_2)	–0.55 V vs. RHE	–14.9 ± 0.8 (CO partial current density)	80% (CO) 20% (H_2)	22
Co–Ce	Co_3O_4–CeO_2 Nanoparticles	10.3 nm particles	Glassy carbon electrode	Aqueous 0.1 M $KHCO_3$ buffer at pH 6.8 (saturated with CO_2)	–0.75 V vs. RHE	–6.1 ($HCOO^-$)	76.4% (HCOOH) 23.6% (CO, H_2,CH_3OH, CH_3CH_2OH, unspecified amounts)	23

Elemental composition	Material	Morphology or size	Supporting electrode	Electrolyte (conditions)	Potential at reported current density	Reported current density (mA cm^{-2})	FE (product)	Ref.
Co–Ni–N–C	$Co_{0.75}Ni_{0.25}$ nanoalloys on N-doped carbon nanofibres	200–300 nm long nanofibres	Glassy carbon electrode	Aqueous 0.5 M $NaHCO_3$ (saturated with CO_2)	–0.9 V vs. RHE	–13.4	85% (CO) 15% (H_2)	24
Nickel								
Ni–N–C	Carbon coated Nickel Nanoparticles	34 nm crystallite size	Glassy carbon electrode	Aqueous 0.5 M $KHCO_3$ buffer (saturated with CO_2)	–0.7 V vs. RHE	–7	93.7% (CO)	25
	Ni and N-doped porous carbon on carbon nanotube hybrid	–	Carbon cloth	Aqueous 0.5 M $KHCO_3$	–0.7 V vs. RHE	–11.2	94% (CO)	26
	Ni-incorporated nitrogen-doped carbon	80 nm Ni NPs with 10 nm N-doped carbon	Carbon substrate	Aqueous 0.1 M $KHCO_3$ buffer at pH 6.8 (saturated with CO_2)	–1.0 V vs. RHE	–3.12	98.4% (CO) 1.6% (H_2)	27
	(Ni, N):C	–	Glassy carbon electrode	Aqueous 0.5 M $KHCO_3$ (saturated with CO_2)	–0.67 V vs. RHE	–3.9	93% (CO) 7% (H_2)	14
	(Ni, N):C	–	Glassy carbon electrode	Aqueous 0.5 M $KHCO_3$ at pH 6.8 (saturated with CO_2)	–0.7 V vs. RHE	–1.1	95% (CO) 5% (H_2)	28
Ni–N–S	Ni NPs dispersed on S-doped nitrogenated carbon	–	Glassy carbon electrode	Aqueous 0.5 M $KHCO_3$ at pH 7.3 (saturated with CO_2)	–0.72 V vs. RHE	–22	97% (CO)	29
Ni–Fe	NiO_x nanoclusters on graphene supported FePc	–	Carbon paper with gas diffusion layer	Aqueous 0.5 M $KHCO_3$ buffer (saturated with CO_2)	–0.4 V vs. RHE	–5.0 (CO partial current density)	86.2 ± 3.2% (CO)	22
Ni–Zn	$Ni_{0.9}Zn_{0.1}O$	–	Glassy carbon electrode	Aqueous 0.5 M $NaHCO_3$ (saturated with CO_2)	–1.4 V vs. Ag/AgCl	–1.4 mA (not normalized to area; electrode area not given)	38.5% (C_2H_4) 18% (H_2) 8.5% (CH_4) < 1.5% (CO)	30

Elemental composition	Material	Morphology or size	Supporting electrode	Electrolyte (conditions)	Potential at reported current density	Reported current density (mA cm^{-2})	FE (product)	Ref.
Ni–Al	Ni_3Al	–	Glassy carbon electrode	Aqueous 0.1 M K_2SO_4 buffered with $KHCO_3$ at pH 4.5 (saturated with CO_2)	–1.38 V vs. Ag/AgCl	–	61% (H_2) 33% (CO) 3% ($CH_3(CH_2)_2OH$) 2% (CH_3OH) 1% ($HCOO^-$)	31
Ni–P	Ni_2P	Spherical morphology 1–20 µm diameter	Aluminium mesh	Aqueous 0.5 M $KHCO_3$ buffer at pH 7.5 (saturated with CO_2)	0.05 V vs. RHE	–0.04	46.3% (H_2) 42.3% (methylglyoxal) 4.65% (2,3-furandiol)	32
	$Ni_{12}P_5$	Spherical morphology 1–20 µm diameter	Aluminium mesh	Aqueous 0.5 M $KHCO_3$ buffer at pH 7.5 (saturated with CO_2)	0.00 V vs. RHE	–0.33	34.6 (H_2) 32.8% (2,3-furandiol) 32.4% (methylglyoxal)	32
	Ni_5P_4	Spherical morphology 1–20 µm diameter	Aluminium mesh	Aqueous 0.5 M $KHCO_3$ buffer at pH 7.5 (saturated with CO_2)	0.05 V vs. RHE	–0.42	45.4% (methylglyoxal) 34.3% (2,3–furandiol) 16.2 (H_2)	32
	NiP_2	Spherical morphology 1–20 µm diameter	Aluminium mesh	Aqueous 0.5 M $KHCO_3$ buffer at pH 7.5 (saturated with CO_2)	–0.05 V vs. RHE	–0.21	61.1% (methylglyoxal) 39.3% (2,3–furandiol)	32
Ni–Ga	NiGa	1–5 µm particle size	Graphite plate	aqueous 0.1 M Na_2CO_3 buffer at pH 6.8 (saturated with CO_2)	–0.48 V vs. RHE	–	96.1% (H_2) 2.5% (CH_4) 1.3% (C_2H_6) 0.1% (C_2H_4)	33
	Ni_3Ga	1–5 µm particle size	Graphite plate	aqueous 0.1 M Na_2CO_3 buffer at pH 6.8 (saturated with CO_2)	–0.48 V vs. RHE	–	98.7% (H_2) 1.2% (CH_4) 0.1% (C_2H_4)	33
	Ni_5Ga_3	1–5 µm particle size	Graphite plate	aqueous 0.1 M Na_2CO_3 buffer at pH 6.8 (saturated with CO_2)	–0.48 V vs. RHE	–	98.5% (H_2) 0.7% (CH_4) 0.6% (C_2H_6) 0.2% (C_2H_4)	33
Palladium								
Pd–Sn	Pd_2Sn	1–5 nm particle size	Carbon paper	Aqueous 0.5 M $KHCO_3$ at pH 7.4 (saturated with CO_2)	–0.43V vs. RHE	–	51% (H_2) 26% ($HCOO^-$) 23% (CO)	34

Elemental composition	Material	Morphology or size	Supporting electrode	Electrolyte (conditions)	Potential at reported current density	Reported current density (mA cm^{-2})	FE (product)	Ref.
Pd–Sn–C	Pd_4Sn NPs on activated carbon	1–5 nm particle size	Carbon paper	Aqueous 0.5 M $KHCO_3$ at pH 7.4 (saturated with CO_2)	–0.43 V vs. RHE	–30	43% ($HCOO^-$) 34% (H_2) 8% (CO)	34
	Pd_3Sn NPs on activated carbon	1–5 nm particle size	Carbon paper	Aqueous 0.5 M $KHCO_3$ at pH 7.4 (saturated with CO_2)	–0.43 V vs. RHE	–25	54% ($HCOO^-$) 26% (H_2) 20% (CO)	34
	Pd_2Sn NPs on activated carbon	1–5 nm particle size	Carbon paper	Aqueous 0.5 M $KHCO_3$ at pH 7.4 (saturated with CO_2)	–0.43 V vs. RHE	–20	63% ($HCOO^-$) 35% (H_2) 9% (CO)	34
	PdSn NPs on activated carbon	1–5 nm particle size	Carbon paper	Aqueous 0.5 M $KHCO_3$ at pH 7.4 (saturated with CO_2)	–0.43 V vs. RHE	–30	99% ($HCOO^-$) 0.3% (CO)	34
	$Pd_{0.5}Sn$ NPs on activated carbon	1–5 nm particle size	Carbon paper	Aqueous 0.5 M $KHCO_3$ at pH 7.4 (saturated with CO_2)	–0.43 V vs. RHE	–33	73% ($HCOO^-$) 22% (H_2) 5% (CO)	34
	$Pd_{0.25}Sn$ NPs on activated carbon	1–5 nm particle size	Carbon paper	Aqueous 0.5 M $KHCO_3$ at pH 7.4 (saturated with CO_2)	–0.43 V vs. RHE	–30	42% ($HCOO^-$) 34% (H_2) 24% (CO)	34
Pd–VN	10wt% Pd in VN (vanadium nitride)	–	Carbon paper	Aqueous 0.5 M $NaHCO_3$ buffer at pH 7.3 (saturated with CO_2)	–0.6 V vs. RHE	–0.025	57.8% (H_2) 28.3% (CO)	35
Pd–Pt	$Pd_{4.5}Pt_{95.5}$	4.4 nm	Carbon	Aqueous 0.1 M phosphate buffer (K_2HPO_4 / 0.1 M KH_2PO_4) at pH 6.7 (saturated with CO_2)	–0.5 V vs. RHE	–1.9	1.5% (HCOOH)	36
	$Pd_{11.5}Pt_{88.5}$	3.8 nm	Carbon	Aqueous 0.1 M phosphate buffer (K_2HPO_4 / 0.1 M KH_2PO_4) at pH 6.7 (saturated with CO_2)	–0.5 V vs. RHE	–2.2	1.7% (HCOOH)	36
	$Pd_{20.9}Pt_{79.1}$	4.1 nm	Carbon	Aqueous 0.1 M phosphate buffer (K_2HPO_4 / 0.1 M KH_2PO_4) at pH 6.7 (saturated with CO_2)	–0.5 V vs. RHE	–2.3	2.6% (HCOOH)	36

Elemental composition	Material	Morphology or size	Supporting electrode	Electrolyte (conditions)	Potential at reported current density	Reported current density (mA cm^{-2})	FE (product)	Ref.
Pd–Pt	$Pd_{4.5}Pt_{95.5}$	4.4 nm	Carbon	Aqueous 0.1 M phosphate buffer (K_2HPO_4 / 0.1 M KH_2PO_4) at pH 6.7 (saturated with CO_2)	−0.5 V vs. RHE	−1.9	1.5% (HCOOH)	36
	$Pd_{39.3}Pt_{60.7}$	3.8 nm	Carbon	Aqueous 0.1 M phosphate buffer (K_2HPO_4 / 0.1 M KH_2PO_4) at pH 6.7 (saturated with CO_2)	−0.5 V vs. RHE	−2.5	12.8% (HCOOH)	36
	$Pd_{49.6}Pt_{50.4}$	4.0 nm	Carbon	Aqueous 0.1 M phosphate buffer (K_2HPO_4 / 0.1 M KH_2PO_4) at pH 6.7 (saturated with CO_2)	−0.5 V vs. RHE	−3.0	27.0% (HCOOH)	36
	$Pd_{59.7}Pt_{40.3}$	3.7 nm	Carbon	Aqueous 0.1 M phosphate buffer (K_2HPO_4 / 0.1 M KH_2PO_4) at pH 6.7 (saturated with CO_2)	−0.5 V vs. RHE	−1.7	35.1% (HCOOH)	36
	$Pd_{70.9}Pt_{29.1}$	4.3 nm	Carbon	Aqueous 0.1 M phosphate buffer (K_2HPO_4 / 0.1 M KH_2PO_4) at pH 6.7 (saturated with CO_2)	−0.5 V vs. RHE	−3.9	58.8% (HCOOH)	36
	$Pd_{78.8}Pt_{21.2}$	4.2 nm	Carbon	Aqueous 0.1 M phosphate buffer (K_2HPO_4 / 0.1 M KH_2PO_4) at pH 6.7 (saturated with CO_2)	−0.5 V vs. RHE	−2.0	39.9% (HCOOH)	36
	$Pd_{88.6}Pt_{11.4}$	4.2 nm	Carbon	Aqueous 0.1 M phosphate buffer (K_2HPO_4 / 0.1 M KH_2PO_4) at pH 6.7 (saturated with CO_2)	−0.5 V vs. RHE	−0.5	18.5% (HCOOH)	36
	$Pd_{94.1}Pt_{5.9}$	4.1 nm	Carbon	Aqueous 0.1 M phosphate buffer (K_2HPO_4 / 0.1 M KH_2PO_4) at pH 6.7 (saturated with CO_2)	−0.5 V vs. RHE	−2.0	35.1% (HCOOH)	36
Pd–Au	$Au_{0.75}Pd_{0.25}$	Thin films (ca. 100 nm thick)	Au–Pd alloy	Aqueous 0.1 M $KHCO_3$ buffer, pH 6.8 (saturated with CO_2)	−0.88 V vs. RHE	−2.4	76% (CO) 13% (H_2) 3% ($HCOO^-$)	37
	$Au_{0.55}Pd_{0.45}$	Thin films (ca. 100 nm thick)	Au–Pd alloy	Aqueous 0.1 M $KHCO_3$ buffer, pH 6.8 (saturated with CO_2)	−0.88 V vs. RHE	−1.8	59% (CO) 16% (H_2) 8% ($HCOO^-$)	37

Elemental composition	Material	Morphology or size	Supporting electrode	Electrolyte (conditions)	Potential at reported current density	Reported current density (mA cm^{-2})	FE (product)	Ref.
Pd–Au	$Au_{0.20}Pd_{0.80}$	Thin films (ca. 100 nm thick)		Aqueous 0.1 M $KHCO_3$ buffer, pH 6.8 (saturated with CO_2)	−0.88 V vs. RHE	−1.3	42% (CO) 31% (H_2) 10% ($HCOO^-$)	37
	4 Pd overlayers on Au	–	Gold electrode	0.1 M KH_2PO_4/0.1 M K_2HPO_4 at pH 6.7 (saturated with CO_2)	−0.6 V vs. RHE	–	73.77% (CO)	38
	$Au_{95}Pd_5$	Ca. 5 nm surface-segregated Pd	Carbon/carbon paper	Aqueous 0.1 M $KHCO_3$ (saturated with CO_2)	−0.5 V vs. RHE	−2.0 (CO partial current density)	80% (CO)	39
Pd–NbN	10 wt% Pd in NbN (Niobium nitride)	–	Carbon paper	Aqueous 0.5 M $NaHCO_3$ buffer at pH 7.3 (saturated with CO_2)	−0.6 V vs. RHE	−0.40	51.9% (H_2) 38.4% (CO)	35
Pd–TaC	10wt% Pd in TaC (tantalum carbide)	Physical vapor deposited 2 ML Pd	TaC thin film	Aqueous 0.5 M $NaHCO_3$ (saturated with CO_2)	−0.6 V vs. RHE	−1.37	50% (CO) 37% (H_2) 13% (unspecified)	40
Pd–NbC	10wt% Pd in NbC (niobium carbide)	Physical vapor deposited 2 ML Pd	NdC thin film	Aqueous 0.5 M $NaHCO_3$ (saturated with CO_2)	−0.6 V vs. RHE	−0.38	65% (H_2) 20% (CO) 15% (unspecified)	40
Pd–Zn	PdZn NPs	3.7 nm	Carbon	Aqueous 0.1 M $KHCO_3$ buffer at pH 6.8 (saturated with CO_2)	−0.4 V vs. RHE	−8.3	94% ($HCOO^-$) 2% (CO)	41
Pd–Ag	$PdAg_3$	4.1 nm	Carbon	Aqueous 0.1 M $KHCO_3$ buffer at pH 6.8 (saturated with CO_2)	−0.8 V vs. RHE	−10.8	96% (CO) 10% (H_2) 4% ($HCOO^-$)	41
	$Ag_{70}Pd_{30}$	Dendrites roughness factor of 47.5	–	Aqueous 0.1 M $KHCO_3$ at pH 6.8 (saturated with CO_2)	−0.8 V vs. RHE	−9.3	98.6% (CO)	42
	$Ag_{15}Pd_{85}$	3.3 ± 0.4 nm	Carbon black	Aqueous 0.1 M $KHCO_3$ (saturated with CO_2)	−0.8 V vs. RHE	−3.3	100.0 ± 4.0% (CO)	43
	Ag-terminated PdAg	25.5 ± 4.9 nm	Carbon paper	Aqueous 0.2 M $NaHCO_3$ (saturated with CO_2)	−0.75 V vs. RHE	−1.0 (CO partial current density)	87.5% (CO)	44
	$Pd_{80}Ag_{20}$	5 – 10 nm	Carbon paper	Aqueous 0.5 M $NaHCO_3$ at pH 7.35 (saturated with CO_2)	−0.9 V vs. RHE	−2.5	70% (CO) 30% (H_2)	45

Elemental composition	Material	Morphology or size	Supporting electrode	Electrolyte (conditions)	Potential at reported current density	Reported current density (mA cm^{-2})	FE (product)	Ref.
Pd–Co	$Pd_{80}Co_{20}$	5 – 10 nm	Carbon paper	Aqueous 0.5 M $NaHCO_3$ at pH 7.35 (saturated with CO_2)	−0.9 V vs. RHE	−2.5	70% (H_2) 30% (CO)	45
Pd–Ni	$Pd_{80}Ni_{20}$	5 – 10 nm	Carbon paper	Aqueous 0.5 M $NaHCO_3$ at pH 7.35 (saturated with CO_2)	−0.9 V vs. RHE	−1.0	55% (H_2) 45% (CO)	45
Pd–Ti	Pd nanoparticles on TiO_2 nanosheets	Mesoporous with 10 nm pore size	Titanium foil	Aqueous 0.5 M $NaHCO_3$ at pH 6.8	−0.1 v vs. RHE	−2.0	88.2% ($HCOO^-$) 11.8% (H_2)	46
Platinum								
Pt–N–C–O	Pt on nitrogenated graphene oxide	100 nm diameter particle size	Glassy carbon electrode	Aqueous 0.1 M KNO_3 at pH 2	−0.30 V vs. RHE	–	41% (CH_3OH)	47
Silver								
Ag–Ti	Ag nanoparticles on TiO_2 nanosheets	< 10 nm Ag NP size	–	Aqueous 0.5 M K_2SO_4 at pH 9.96 (saturated with CO_2)	−1.68 V vs. Ag/AgCl	−101 (CO)	92% (CO) 8% (H_2)	48
Ag–Co	Ag–Co	20 nm particle size	Gas diffusion layer	Aqueous 0.5 M $KHCO_3$ buffer (saturated with CO_2)	−2.0 V vs. Ag/AgCl	−94	69.5% (H_2) 19.5% (CH_4) 8% (CO) 3% (C_2H_4)	49
Ag–Zn	Zn dendrites on Ag foam	20–50 µm pores	Ag disk	Aqueous 0.1 M $KHCO_3$ (saturated with CO_2)	−1.41 V vs. RHE	−26	54.4% (H_2) 19.7% (CO) 10.5 % (CH_3OH) 5.9% (CH_4) 4.0% ($HCOO^-$)	50
	Ag_5Zn_8	0.1 mm polycrystalline foil	–	Aqueous 0.1 M $KHCO_3$ buffer at pH 6.8 (saturated with CO_2)	−1.2 V vs. Ag/AgCl	−3.9	65% (CO) 25% (H_2) 5% ($HCOO^-$)	51
Ag–Sn	Ag_3Sn core with SnO_x shell	Ag_3Sn core with 2 nm amorphous metal oxide layer	Carbon paper	Aqueous 0.5 M $NaHCO_3$ at pH 7.2 (Saturated with CO_2)	−0.8 V vs. RHE	−16	80% ($HCOO^-$) 20% (CO)	52
Ag–Cl	Ag NPs with surface Cl	–	Carbon fibre	Aqueous 0.5 M $KHCO_3$ buffer at pH 7.2 (saturated with CO_2)	−0.8 V vs. RHE	−9.4	98% (CO)	53

Elemental composition	Material	Morphology or size	Supporting electrode	Electrolyte (conditions)	Potential at reported current density	Reported current density (mA cm^{-2})	FE (product)	Ref.
Ag–Br	Ag NPs with surface Br	–	Silver foil	Aqueous 0.1 M $KHCO_3$ buffer at 6.8	−0.6 V vs. RHE	−2.48 (CO partial current density)	95% (CO) 5% (H_2)	54
Ag–I	Ag NPs with surface iodine	–	Silver foil	Aqueous 0.1 M $KHCO_3$ buffer at 6.8	−0.6 V vs. RHE	−0.86 (CO partial current density)	72% (CO) 28% (H_2)	54
	Iodide-derived (ID) Ag	Porous	Silver foil	Aqueous 0.5 M $KHCO_3$ (saturated with Co_2)	−0.7 V vs. RHE	−16.7	94.5% (CO)	55
Gold								
Au–Ag–Zn	AuAg NPs on ZnO support	10 nm	ZnO	Aqueous 0.1 M $KHCO_3$ (saturated with CO_2)	−0.4 V vs. RHE	−0.3	94.7% (CO) 2.6% (H_2)	56
Au–Sn	$Au_{0.9}Sn_{0.1}$	Thin films	Titanium foil	Aqueous 0.1 M $KHCO_3$ (saturated with CO_2)	−1.61 V vs. Ag/AgCl	−10	99% (H_2) 6% ($HCOO^-$) 3% (CO)	57
	Au_2Sn	23.0 ± 2.9 nm	Glassy carbon	Aqueous 0.1 M $NaHCO_3$ (saturated with CO_2)	−1.0 V vs. RHE	−6.5	59% (H_2) 28% (HCOOH) 6% (CO)	58
	AuSn	31.8 ± 3.9 nm	Glassy carbon	Aqueous 0.1 M $NaHCO_3$ (saturated with CO_2)	−1.0 V vs. RHE	−6.0	71% (H_2) 22% (HCOOH) 6% (CO)	58
	$AuSn_2$	32.4 ± 3.7 nm	Glassy carbon	Aqueous 0.1 M $NaHCO_3$ (saturated with CO_2)	−1.0 V vs. RHE	−6.0	55% (H_2) 35% (HCOOH) 10% (CO)	58
	$AuSn_4$	33.0 ± 2.5 nm	Glassy carbon	Aqueous 0.1 M $NaHCO_3$ (saturated with CO_2)	−1.0 V vs. RHE	−3.5	65% (HCOOH) 28% (H_2) 7% (CO)	58
	0.1 monolayer thick Sn deposited Au(110) surfaces	Single crystal plane with metal deposition	Au(110)	Aqueous 0.1 M $KHCO_3$ (saturated with CO_2)	−0.80 V vs. RHE	−1.5 (CO partial current density) −2.1 (H_2 partial current density)	43% (CO)	59

Elemental composition	Material	Morphology or size	Supporting electrode	Electrolyte (conditions)	Potential at reported current density	Reported current density (mA cm^{-2})	FE (product)	Ref.
Au–Pb	Au decorated Pb	42 ± 5 nm	Glassy carbon electrode	Aqueous 0.5 M $KHCO_3$ buffer at pH 7.2 (saturated with CO_2)	−1.07 V vs. RHE	−10.8 ± 0.5	25.7 ± 8.0% (CO) 25.5 ± 0.7% (HCOOH) 2.8 ± 0.4% (CH_4)	60
Au–Co	0.1 monolayer-thick-Co deposited Au(110) surfaces	Single crystal plane with metal deposition	Au(110)	Aqueous 0.1 M $KHCO_3$ (saturated with CO_2)	−0.60 V vs. RHE	−1.2 (CO partial current density) −0.1 (H_2 partial current density)	87 % (CO)	59
Au–Ni	AuNi	14–5.5 nm particle size	Carbon nanofibre membrane	Aqueous 0.1 M $KHCO_3$ at pH 6.8 (saturated with CO_2)	−0.98 V vs. RHE	−4.0 (CO partial current density)	92% (CO) 8% (H_2)	61
Au–Fe	AuFe core with Au shell	Core shell nanoparticle	Glassy carbon electrode	Aqueous 0.5 M $KHCO_3$ at pH 7.2 (saturated with CO_2)	−0.4 V vs. RHE	−11.05	97.6% (CO) 2.4% (H_2)	62
Zinc								
Zn–N	Zn–coordinated N-doped carbon	–	Carbon cloth	Aqueous 0.5 M $KHCO_3$ at pH 7.33 (saturated with CO_2)	−0.5 V vs. RHE	−5.0	95% (CO) 5% (H_2)	63
	ZnN_4 on carbon support	–	Carbon paper	Aqueous 0.5 M $KHCO_3$ at pH 7.2 (saturated with CO_2)	−0.73 V vs. RHE	−13.62	95% (CO)	64
Zn–S	ZnS	3.9 nm thick nanosheets	FTO glass	Aqueous 0.1 M $KHCO_3$ buffer at pH 6.8 (saturated with CO_2)	−0.8 V vs. RHE	−4.28	94.2% (CO) 5.8% (H_2)	65
Zn–Sn	Sn–Zn	Electrodeposited film	4-Amino-pyridine immobilized on carbon paper	Aqueous 0.1 M $KHCO_3$ (saturated with CO_2)	−0.5 V vs. RHE	−2.0	59.9% (CH_3OH) 21% (H_2) 11% (CO)	66
Zn–In	$Zn_{0.95}In_{0.05}$	Ca. 50 nm	Glassy carbon electrode	Aqueous 0.5 M $KHCO_3$ (saturated with CO_2)	−1.2 V vs. RHE	−22	95% (HCOOH) 3% (CO) 2% (H_2)	67

Elemental composition	Material	Morphology or size	Supporting electrode	Electrolyte (conditions)	Potential at reported current density	Reported current density (mA cm^{-2})	FE (product)	Ref.
Zn–Ga	$ZnGa_2O_4$	5–10 nm crystals with 3.8 nm pore size	Titanium sheet	Aqueous 0.1 M $KHCO_3$ buffer at pH 6.82 (saturated with CO_2)	–0.8 V vs. RHE	–0.55	96% (CO) 4% (H_2)	68
Zn–Bi	$ZnBi_3$ NPs	Irregular plates (ca. 500 nm)	Zinc foil	Aqueous 0.5 M $NaHCO_3$ (saturated with CO_2)	–0.8 V vs. RHE	–3.8	94% (HCOOH)	69
Cadmium								
Cd–S	CdS	nanorods	Titanium substrate	Aqueous 0.5 M $KHCO_3$ (saturated with CO_2)	–0.9 V vs. RHE	–1.5	95% (CO)	70
	CdS	nanorods	Carbon paper	Aqueous 0.1 M $KHCO_3$	–1.2 V vs. RHE	–27.1	81% (CO) 19% (H_2)	71
Gallium								
Ga–As	GaAs (111), arsenide capped	Single crystal plane	–	Aqueous 0.2 M Na_2SO_4 at pH 4 (saturated with CO_2)	–1.2–1.4 V vs. SCE	–0.20	1% (CH_3OH)	72
	GaAs (111), gallium capped	Single crystal plane	–	Aqueous 0.2 M Na_2SO_4 at pH 4 (saturated with CO_2)	–1.2–1.4 V vs. SCE	–0.29–0.34	0.27–0.14% (CH_3OH)	72
	GaAs (111), gallium capped	Single crystal plane	–	Aqueous 0.2 M Na_2SO_4 at pH 4 (saturated with CO_2)	–1.2–1.4 V vs. SCE	–0.34	0.30–0.80% (CH_3OH)	72
	GaAs (110), gallium capped	Single crystal plane	–	Aqueous 0.2 M Na_2SO_4 at pH 4 (saturated with CO_2)	–1.2–1.4 V vs. SCE	–0.13	0.14% (CH_3OH)	72
	GaAs (110), gallium capped	Single crystal plane	–	Aqueous 0.2 M Na_2SO_4 at pH 4 (saturated with CO_2)	–1.2–1.4 V vs. SCE	–0.15–0.24	0.04% (CH_3OH)	72
Tin								
Sn–Al	SnO_2 NPs with Al_2O_3 support	–	Carbon fibre paper	Aqueous 0.5 M $KHCO_3$ (saturated with CO_2)	–2.0 V vs. Ag/AgCl	–21.7 ($HCOO^-$ partial current density)	65% ($HCOO^-$) 35% (H_2)	73
Sn–Pd	SnO_2 nanoparticles on Pd nanosheets	3 – 5 nm (NPs) ca. 1 nm thick (nanosheets)	Carbon paper	Aqueous 0.1 M $KHCO_3$ at pH 6.8 (saturated with CO_2)	–0.24 V vs. RHE	–1.45	54.8 ± 2 % (CH_3OH) 40% (H_2) 7% ($HCOO^-$)	74
Sn–S	SnS on Au nanoneedles	5 nm grain size	Carbon paper	Aqueous 0.1 M $KHCO_3$ (saturated with CO_2)	–0.75 V vs. RHE	–55	93% (HCOOH)	75
Sn–Ti	$Sn_{0.3}Ti_{0.7}O_2$	5 nm particle size	Carbon paper	Aqueous 0.5 M $KHCO_3$	–0.54 V vs. RHE	–3.91	94.5% (CO) 5.5% (H_2)	76

Elemental composition	Material	Morphology or size	Supporting electrode	Electrolyte (conditions)	Potential at reported current density	Reported current density (mA cm^{-2})	FE (product)	Ref.
Sn–N–C	Sn single atom on N-doped carbon	–	Glassy carbon electrode	Aqueous 0.25 M $KHCO_3$ buffer at pH 7.1 (saturated with CO_2)	–1.6 V vs. SCE	–11.7	74.3% (HCOOH)	77
Sn–Pb–Sb	Sn–Pb–Sb	Alloy foil	Alloy foil	Aqueous 0.1 M $KHCO_3$ at pH 8.4 (saturated with CO_2)	–1.4 V vs. Ag/AgCl	–8.5	91% ($HCOO^-$) 9% (unspecified)	78
Sn–Pb	$Sn_{75}Pb_{25}$	Electro-deposited from fluoroborate salt bath	Carbon cloth	Aqueous 0.5 M $KHCO_3$ (saturated with CO_2)	−2.0 V vs. Ag/AgCl	–25	Ca. 60% ($HCOO^-$)	79
	$Sn_{75}Pb_{25}$	Electro-deposited from fluoroborate salt bath	Teflonated carbon paper	Aqueous 0.5 M $KHCO_3$ (saturated with CO_2)	−2.0 V vs. Ag/AgCl	–17	90–95 % ($HCOO^-$)	79
	$Sn_{77.3}Pb_{22.7}$	2–3 µm in diameter	Carbon paper	Aqueous 0.5 M $KHCO_3$ buffer (saturated with CO_2)	–2.0 V vs. Ag/AgCl	–45	78% ($HCOO^-$) 22% (H_2)	80
	$Sn_{56.3}Pb_{43.7}$	2–3 µm in diameter	Carbon paper	Aqueous 0.5 M $KHCO_3$ buffer (saturated with CO_2)	–2.0 V vs. Ag/AgCl	–45.7	79.8% ($HCOO^-$) 18.7% (H_2)	80
	$Sn_{35.1}Pb_{64.9}$	2–3 µm in diameter	Carbon paper	Aqueous 0.5 M $KHCO_3$ buffer (saturated with CO_2)	–2.0 V vs. Ag/AgCl	–40	75% ($HCOO^-$) 25% (H_2)	80
Sn–Bi	$Sn_{80}Bi_{20}$ core with Bi-SnO_x shells	19.9 ± 1.2 nm	YLS–29BC gas diffusion layer	Aqueous 0.5 M $KHCO_3$ (saturated with CO_2, gas diffusion flow cell)	−0.88 V vs. RHE	–20.9 ($HCOO^-$ partial current density)	95.8% (HCOOH) 4.2% (H_2)	81
Lead								
Pb–Cl	Pb NPs with surface Cl	–	Carbon fibre	Aqueous 0.5 M $KHCO_3$ buffer at pH 7.2 (saturated with CO_2)	−1.0 V vs. RHE	–10	90% (HCOOH)	53
Bismuth								
Bi–Te	Bi_2Te_3	16 nm thick hexagonal NPs	Glassy carbon electrode	Aqueous 0.5 M $NaHCO_3$ (saturated with CO_2)	−0.9 V vs. RHE	–15	89.6% (HCOOH) 10.4% (CO and H_2)	82
Bi–C	Bi NP anchored on Carbon nanotubes	4.4 nm particle diameter	Carbon paper	Aqueous 0.5 M $KHCO_3$ buffer at pH 7.3 (saturated with CO_2)	–1.5 V vs. SCE	–10.7	95.2% (HCOOH)	83

Elemental composition	Material	Morphology or size	Supporting electrode	Electrolyte (conditions)	Potential at reported current density	Reported current density (mA cm^{-2})	FE (product)	Ref.
Bi–C	Bi NPs on Bi_2O_3 nanosheets	800 nm thick nanosheets	Glassy carbon electrode	Aqueous 0.5 M $NaHCO_3$ (saturated with CO_2)	−0.86 V vs. RHE	–24.4 ($HCOO^-$ partial current density)	~100% ($HCOO^-$)	84
Bi–Br	BiOBr	–	Carbon paper	Aqueous 0.1 M $KHCO_3$ (saturated with CO_2)	–0.95 V vs. RHE	–80	99% ($HCOO^-$)	85
	BiOBr	–	Carbon paper	Aqueous 2 M $KHCO_3$ (gas diffusion cell)	–	–200	90% ($HCOO^-$) 10% (H_2)	85

References

1. M.-G. Kim, J. Jeong, Y. Choi, J. Park, E. Park, C.-H. Cheon, N.-K. Kim, B. K. Min and W. Kim, *ACS Appl. Mater. Interfaces*, 2020, **12**, 11890-11897.
2. F. Pan, W. Deng, C. Justiniano and Y. Li, *Appl. Catal. B*, 2018, **226**, 463-472.
3. X. Sun, Q. Zhu, X. Kang, H. Liu, Q. Qian, Z. Zhang and B. Han, *Angew. Chem. Int. Ed.*, 2016, **55**, 6771-6775.
4. X. Sun, L. Lu, Q. Zhu, C. Wu, D. Yang, C. Chen and B. Han, *Angew. Chem. Int. Ed.*, 2018, **57**, 2427-2431.
5. 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.
6. M. Asadi, B. Kumar, A. Behranginia, B. A. Rosen, A. Baskin, N. Repnin, D. Pisasale, P. Phillips, W. Zhu, R. Haasch, R. F. Klie, P. Král, J. Abiade and A. Salehi-Khojin, *Nat. Comm.*, 2014, **5**, 4470.
7. K. Sun, Y. Ji, Y. Liu and Z. Wang, *J. Mater. Chem. A*, 2020, **8**, 12291-12295.
8. Y. Oh and X. Hu, *Chem. Commun.*, 2015, **51**, 13698-13701.
9. *ECS Meeting Abstracts*, 2016, DOI: 10.1149/ma2016-02/46/3336.
10. M. Asadi, K. Kim, C. Liu, A. V. Addepalli, P. Abbasi, P. Yasaei, P. Phillips, A. Behranginia, J. M. Cerrato, R. Haasch, P. Zapol, B. Kumar, R. F. Klie, J. Abiade, L. A. Curtiss and A. Salehi-Khojin, *Science*, 2016, **353**, 467.
11. B. Zhang, J. Zhang, J. Shi, D. Tan, L. Liu, F. Zhang, C. Lu, Z. Su, X. Tan, X. Cheng, B. Han, L. Zheng and J. Zhang, *Nat. Comm.*, 2019, **10**, 2980.
12. A. S. Varela, N. Ranjbar Sahraie, J. Steinberg, W. Ju, H.-S. Oh and P. Strasser, *Angew. Chem. Int. Ed.*, 2015, **54**, 10758-10762.
13. T. N. Huan, N. Ranjbar, G. Rousse, M. Sougrati, A. Zitolo, V. Mougel, F. Jaouen and M. Fontecave, *ACS Catal.*, 2017, **7**, 1520-1525.
14. X.-M. Hu, H. H. Hval, E. T. Bjerglund, K. J. Dalgaard, M. R. Madsen, M.-M. Pohl, E. Welter, P. Lamagni, K. B. Buhl, M. Bremholm, M. Beller, S. U. Pedersen, T. Skrydstrup and K. Daasbjerg, *ACS Catal.*, 2018, **8**, 6255-6264.
15. S. Zhao, S. Guo, C. Zhu, J. Gao, H. Li, H. Huang, Y. Liu and Z. Kang, *RSC Adv.*, 2017, **7**, 1376-1381.
16. L. Ji, L. Li, X. Ji, Y. Zhang, S. Mou, T. Wu, Q. Liu, B. Li, X. Zhu, Y. Luo, X. Shi, A. M. Asiri and X. Sun, *Angew. Chem. Int. Ed.*, 2020, **59**, 758-762.
17. L. Ji, L. Chang, Y. Zhang, S. Mou, T. Wang, Y. Luo, Z. Wang and X. Sun, *ACS Catal.*, 2019, **9**, 9721-9725.
18. K. Pellumbi, M. Smialkowski, D. Siegmund and U.-P. Apfel, *Chem. Eur. J.*, 2020, **26**, 9938-9944.
19. N. Furuya, T. Yamazaki and M. Shibata, *J. Electroanal. Chem.*, 1997, **431**, 39-41.
20. Y. Xia, S. Kashtanov, P. Yu, L.-Y. Chang, K. Feng, J. Zhong, J. Guo and X. Sun, *Nano Energy*, 2020, **67**, 104163.
21. F. Pan, A. Liang, Y. Duan, Q. Liu, J. Zhang and Y. Li, *J. Mater. Chem. A*, 2017, **5**, 13104-13111.
22. Y. Cheng, J.-P. Veder, L. Thomsen, S. Zhao, M. Saunders, R. Demichelis, C. Liu, R. De Marco and S. P. Jiang, *J. Mater. Chem. A*, 2018, **6**, 1370-1375.
23. Q. Zhang, J. Du, A. He, Z. Liu and C. Tao, *J. Solid State Chem.*, 2019, **279**, 120946.
24. W. Zhang, J. Zeng, H. Liu, Z. Shi, Y. Tang and Q. Gao, *J. Catal.*, 2019, **372**, 277-286.
25. M. Jia, C. Choi, T.-S. Wu, C. Ma, P. Kang, H. Tao, Q. Fan, S. Hong, S. Liu, Y.-L. Soo, Y. Jung, J. Qiu and Z. Sun, *Chem. Sci.*, 2018, **9**, 8775-8780.
26. S. Ye, G. Fan, J. Xu, L. Yang and F. Li, *Electrochim. Acta*, 2020, **334**, 135583.
27. Z. Peng, Y. Huang, J. Wang, R. Yang, J. Xie and Y. Wang, *ChemElectroChem*, 2020, **7**, 1142-1148.
28. P. Su, K. Iwase, S. Nakanishi, K. Hashimoto and K. Kamiya, *Small*, 2016, **12**, 6083-6089.
29. H. B. Yang, S.-F. Hung, S. Liu, K. Yuan, S. Miao, L. Zhang, X. Huang, H.-Y. Wang, W. Cai, R. Chen, J. Gao, X. Yang, W. Chen, Y. Huang, H. M. Chen, C. M. Li, T. Zhang and B. Liu, *Nat. Energy*, 2018, **3**, 140-147.
30. S. Nellaiappan and S. Sharma, *ACS Appl. Energy Mater.*, 2019, **2**, 2998-3003.
31. A. R. Paris and A. B. Bocarsly, *Faraday Discuss.*, 2019, **215**, 192-204.
32. K. U. D. Calvinho, A. B. Laursen, K. M. K. Yap, T. A. Goetjen, S. Hwang, N. Murali, B. Mejia-Sosa, A. Lubarski, K. M. Teeluck, E. S. Hall, E. Garfunkel, M. Greenblatt and G. C. Dismukes, *Energy Environ. Sci.*, 2018, **11**, 2550-2559.
33. D. A. Torelli, S. A. Francis, J. C. Crompton, A. Javier, J. R. Thompson, B. S. Brunschwig, M. P. Soriaga and N. S. Lewis, *ACS Catal.*, 2016, **6**, 2100-2104.
34. X. Bai, W. Chen, C. Zhao, S. Li, Y. Song, R. Ge, W. Wei and Y. Sun, *Angew. Chem. Int. Ed.*, 2017, **56**, 12219-12223.
35. Y. Liu, D. Tian, A. N. Biswas, Z. Xie, S. Hwang, J. H. Lee, H. Meng and J. G. Chen, *Angew. Chem. Int. Ed.*, 2020, **59**, 11345-11348.
36. R. Kortlever, I. Peters, S. Koper and M. T. M. Koper, *ACS Catal.*, 2015, **5**, 3916-3923.
37. C. Hahn, D. N. Abram, H. A. Hansen, T. Hatsukade, A. Jackson, N. C. Johnson, T. R. Hellstern, K. P. Kuhl, E. R. Cave, J. T. Feaster and T. F. Jaramillo, *J. Mater. Chem. A*, 2015, **3**, 20185-20194.
38. R. Kortlever, I. Peters, C. Balemans, R. Kas, Y. Kwon, G. Mul and M. T. M. Koper, *Chem. Commun.*, 2016, **52**, 10229-10232.
39. Y. Wang, L. Cao, N. J. Libretto, X. Li, C. Li, Y. Wan, C. He, J. Lee, J. Gregg, H. Zong, D. Su, J. T. Miller, T. Mueller and C. Wang, *J. Am. Chem. Soc.*, 2019, **141**, 16635-16642.
40. J. Wang, S. Kattel, C. J. Hawxhurst, J. H. Lee, B. M. Tackett, K. Chang, N. Rui, C.-J. Liu and J. G. Chen, *Angew. Chem. Int. Ed.*, 2019, **58**, 6271-6275.
41. T. Gunji, H. Ochiai, T. Ohira, Y. Liu, Y. Nakajima and F. Matsumoto, *Chem. Mater.*, 2020, DOI: 10.1021/acs.chemmater.0c01137.

42. J. Han, S. Li, J. Chen, Y. Liu, D. Geng, D. Wang and L. Zhang, *ChemElectroChem*, 2020, **7**, 2608-2613.
43. M. Cui, G. Johnson, Z. Zhang, S. Li, S. Hwang, X. Zhang and S. Zhang, *Nanoscale*, 2020, **12**, 14068-14075.
44. R. Lin, X. Ma, W.-C. Cheong, C. Zhang, W. Zhu, J. Pei, K. Zhang, B. Wang, S. Liang, Y. Liu, Z. Zhuang, R. Yu, H. Xiao, J. Li, D. Wang, Q. Peng, C. Chen and Y. Li, *Nano Res.*, 2019, **12**, 2866-2871.
45. J. H. Lee, S. Kattel, Z. Jiang, Z. Xie, S. Yao, B. M. Tackett, W. Xu, N. S. Marinkovic and J. G. Chen, *Nat. Comm.*, 2019, **10**, 3724.
46. J. Zou, M. Iqbal, A. Vijayakumar, C. Wang, D. R. Macfarlane, Y. Yamauchi, C.-Y. Lee and G. G. Wallace, *J. Mater. Chem. A*, 2020, **8**, 8041-8048.
47. A. A. Ensafi, H. A. Alinajafi and B. Rezaei, *J. Electroanal. Chem.*, 2016, **783**, 82-89.
48. S. Ma , Y. Lan , G. M. J. Perez, S. Moniri and P. J. A. Kenis *ChemSusChem*, 2014, **7**, 866-874.
49. S. Singh, R. K. Gautam, K. Malik and A. Verma, *J. CO2 Util.*, 2017, **18**, 139-146.
50. Q. H. Low, N. W. X. Loo, F. Calle-Vallejo and B. S. Yeo, *Angew. Chem. Int. Ed.*, 2019, **58**, 2256-2260.
51. T. Hatsukade, K. P. Kuhl, E. R. Cave, D. N. Abram, J. T. Feaster, A. L. Jongerius, C. Hahn and T. F. Jaramillo, *Energy Technol.*, 2017, **5**, 955-961.
52. W. Luc, C. Collins, S. Wang, H. Xin, K. He, Y. Kang and F. Jiao, *J. Am. Chem. Soc.*, 2017, **139**, 1885-1893.
53. H. Q. Fu, L. Zhang, L. R. Zheng, P. F. Liu, H. Zhao and H. G. Yang, *J. Mater. Chem. A*, 2019, **7**, 12420-12425.
54. Y.-C. Hsieh, L. E. Betancourt, S. D. Senanayake, E. Hu, Y. Zhang, W. Xu and D. E. Polyansky, *ACS Appl. Energy Mater.*, 2019, **2**, 102-109.
55. Y. Zhang, L. Ji, W. Qiu, X. Shi, A. M. Asiri and X. Sun, *Chem. Commun.*, 2018, **54**, 2666-2669.
56. M. Sarno, E. Ponticorvo, S. Piotto, A. M. Nardiello, S. De Pasquale and N. Funicello, *J. CO2 Util.*, 2020, **39**, 101179.
57. S. Chandrashekar, N. T. Nesbitt and W. A. Smith, *J. Phys. Chem. C*, 2020, **124**, 14573-14580.
58. A. M. Ismail, G. F. Samu, Á. Balog, E. Csapó and C. Janáky, *ACS Energy Lett.*, 2019, **4**, 48-53.
59. N. Todoroki, H. Tei, T. Miyakawa, H. Tsurumaki and T. Wadayama, *ChemElectroChem*, 2019, **6**, 3101-3107.
60. A. M. Ismail, G. F. Samu, H. C. Nguyën, E. Csapó, N. López and C. Janáky, *ACS Catal.*, 2020, **10**, 5681-5690.
61. J. Hao, H. Zhu, Y. Li, P. Liu, S. Lu, F. Duan, W. Dong, Y. Lu, T. Liu and M. Du, *Chem. Eng. J.*, 2020, **404**, 126523.
62. K. Sun, T. Cheng, L. Wu, Y. Hu, J. Zhou, A. Maclennan, Z. Jiang, Y. Gao, W. A. Goddard and Z. Wang, *J. Am. Chem. Soc.*, 2017, **139**, 15608-15611.
63. Z. Chen, K. Mou, S. Yao and L. Liu, *ChemSusChem*, 2018, **11**, 2944-2952.
64. F. Yang, P. Song, X. Liu, B. Mei, W. Xing, Z. Jiang, L. Gu and W. Xu, *Angew. Chem. Int. Ed.*, 2018, **57**, 12303-12307.
65. 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.
66. W. Huang and G. Yuan, *Electrochem. Commun.*, 2020, **118**, 106789.
67. I. S. Kwon, T. T. Debela, I. H. Kwak, H. W. Seo, K. Park, D. Kim, S. J. Yoo, J.-G. Kim, J. Park and H. S. Kang, *J. Mater. Chem. A*, 2019, **7**, 22879-22883.
68. M. Zhao, Y. Gu, P. Chen, Z. Xin, H. Zhu, B. Wang, K. Zhu, S. Yan and Z. Zou, *J. Mater. Chem. A*, 2019, **7**, 9316-9323.
69. T. Zhang, Y. Qiu, P. Yao, X. Li and H. Zhang, *ACS Sustain. Chem. Eng.*, 2019, **7**, 15190-15196.
70. 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.
71. R. He, A. Zhang, Y. Ding, T. Kong, Q. Xiao, H. Li, Y. Liu and J. Zeng, *Adv. Mater.*, 2018, **30**, 1705872.
72. D. Canfield, *J. Electrochem. Soc.*, 1983, **130**, 1772.
73. Y. E. Kim, W. Lee, M. H. Youn, S. K. Jeong, H. J. Kim, J. C. Park and K. T. Park, *J. Ind. Eng. Chem.*, 2019, **78**, 73-78.
74. W. Zhang, Q. Qin, L. Dai, R. Qin, X. Zhao, X. Chen, D. Ou, J. Chen, T. T. Chuong, B. Wu and N. Zheng, *Angew. Chem. Int. Ed.*, 2018, **57**, 9475-9479.
75. X. Zheng, P. De Luna, F. P. García 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.
76. G. Wen, B. Ren, M. G. Park, J. Yang, H. Dou, Z. Zhang, Y.-P. Deng, Z. Bai, L. Yang, J. Gostick, G. A. Botton, Y. Hu and Z. Chen, *Angew. Chem. Int. Ed.*, 2020, **59**, 12860-12867.
77. X. Zu, X. Li, W. Liu, Y. Sun, J. Xu, T. Yao, W. Yan, S. Gao, C. Wang, S. Wei and Y. Xie, *Adv. Mater.*, 2019, **31**, 1808135.
78. S. Rasul, A. Pugnant, H. Xiang, J.-M. Fontmorin and E. H. Yu, *J. CO2 Util.*, 2019, **32**, 1-10.
79. C. E. Moore and E. L. Gyenge, *ChemSusChem*, 2017, **10**, 3512-3519.
80. S. Y. Choi, S. K. Jeong, H. J. Kim, I.-H. Baek and K. T. Park, *ACS Sustain. Chem. Eng.*, 2016, **4**, 1311-1318.
81. Q. Yang, Q. Wu, Y. Liu, S. Luo, X. Wu, X. Zhao, H. Zou, B. Long, W. Chen, Y. Liao, L. Li, P. K. Shen, L. Duan and Z. Quan, *Adv. Mater.*, 2020, DOI: 10.1002/adma.202002822.
82. N. Zhang, F. Zheng, B. Huang, Y. Ji, Q. Shao, Y. Li, X. Xiao and X. Huang, *Adv. Mater.*, 2020, **32**, 1906477.
83. X. Zhang, J. Fu, Y. Liu, X.-D. Zhou and J. Qiao, *ACS Sustain. Chem. Eng.*, 2020, **8**, 4871-4876.
84. L. Li, D.-K. Ma, F. Qi, W. Chen and S. Huang, *Electrochim. Acta*, 2019, **298**, 580-586.
85. F. P. García de Arquer, O. S. Bushuyev, P. De Luna, C.-T. Dinh, A. Seifitokaldani, M. I. Saidaminov, C.-S. Tan, L. N. Quan, A. Proppe, M. G. Kibria, S. O. Kelley, D. Sinton and E. H. Sargent, *Adv. Mater.*, 2018, **30**, 1802858.