Electronic Supplementary Information

A review of hetero-structured Ni-based active catalysts for urea electrolysis

Jiaxin Li[ab], Shuli Wang[b], Sijia Sun[a], Xiang Wu[c], Baogang Zhang[*a] and Ligang Feng[*b]

[a] School of Water Resources and Environment, MOE Key Laboratory of Groundwater Circulation and Environmental Evolution, China University of Geosciences (Beijing), Beijing 100083, P. R. China. E-mail: baogangzhang@cugb.edu.cn

[b] School of Chemistry and Chemical Engineering, Yangzhou University, Yangzhou 225002, P. R. China. E-mail: ligang.feng@yzu.edu.cn; fenglg11@gmail.com

[c] School of Materials Science and Engineering, Shenyang University of Technology, Shenyang 110870, Liaoning, China

Table S1. Proposed reaction mechanisms for urea electrooxidation reaction (M=NiOOH).[1] Copyright (2010) American Chemical Society.

Steps	Reaction pathway
	Path 1
1	$CO(NH_2)_2 + M \rightarrow [M{\cdot}CO(NH_2)_2]_{ads}$
2	$[M{\cdot}CO(NH_2)_2]_{ads} + OH^- \rightarrow [M{\cdot}CO(NH_2{\cdot}NH)]_{ads} + H_2O + e^{-a}$
3	$[M{\cdot}CO(NH_2{\cdot}NH)]_{ads} + OH^- \rightarrow [M{\cdot}CONH_2N]_{ads} + H_2O + e^{-a}$
4	$[M{\cdot}CO(NH_2N)]_{ads} + OH^- \rightarrow [M{\cdot}CONHN]_{ads} + H_2O + e^{-a}$
5	$[M{\cdot}CONHN]_{ads} + OH^- \rightarrow [M{\cdot}CO{\cdot}N_2]_{ads} + H_2O + e^{-a}$
6	$[M{\cdot}CO{\cdot}N_2]_{ads} + OH^- \rightarrow [M{\cdot}CO{\cdot}OH]_{ads} + N_2 + e^-$
7	$[M{\cdot}CO{\cdot}OH]_{ads} + OH^- \rightarrow [M{\cdot}CO_2]_{ads} + H_2O + e^-$
8	$[M{\cdot}CO_2]_{ads} \rightarrow M + CO_2$
	Path 2
1	$CO(NH_2)_2 + M \rightarrow [M{\cdot}CO(NH_2)_2]_{ads}$
2	$[M{\cdot}CO(NH_2)_2]_{ads} + OH^- \rightarrow [M{\cdot}CO(NH_2{\cdot}NH)]_{ads} + H_2O + e^{-b}$
3	$[M{\cdot}CO(NH_2{\cdot}NH)]_{ads} + OH^- \rightarrow [M{\cdot}CONH_2N]_{ads} + H_2O + e^{-b}$
4	$[M{\cdot}CO(NH_2N)]_{ads} + OH^- \rightarrow [M{\cdot}CONHN]_{ads} + H_2O + e^{-b}$
5	$[M{\cdot}CO{\cdot}NHN]_{ads} + OH^- \rightarrow [M{\cdot}CO{\cdot}N_2]_{ads} + H_2O + e^{-b}$
6	$[M{\cdot}CO{\cdot}N_2]_{ads} + OH^- \rightarrow [M{\cdot}CO{\cdot}OH]_{ads} + N_2 + e^-$
7	$[M{\cdot}CO{\cdot}OH]_{ads} + OH^- \rightarrow [M{\cdot}CO_2]_{ads} + H_2O + e^-$
8	$[M{\cdot}CO_2]_{ads} \rightarrow M + CO_2$
	Path 3
1	$CO(NH_2)_2 + M \rightarrow [M{\cdot}CO(NH_2)_2]_{ads}$
2	$[M{\cdot}CO(NH_2)_2]_{ads} + OH^- \rightarrow [M{\cdot}CO(NH_2{\cdot}NH)]_{ads} + H_2O + e^{-b}$
3	$[M{\cdot}CO{\cdot}NH_2NH)]_{ads} + OH^- \rightarrow [M{\cdot}CONH{\cdot}NH]_{ads} + H_2O + e^{-b}$
4	$[M{\cdot}CO{\cdot}NHNH]_{ads} + OH^- \rightarrow M{\cdot}CO + NH{\cdot}N + H_2O + e^{-b}$
5	$[M{\cdot}CO{\cdot}NHN]_{ads} + OH^- \rightarrow M{\cdot}CO{\cdot}N_2 + H_2O + e^{-b}$
6	$[M{\cdot}CO{\cdot}N_2]_{ads} + OH^- \rightarrow [M{\cdot}CO{\cdot}OH]_{ads} + N_2 + e^-$
7	$[M{\cdot}CO{\cdot}OH]_{ads} + OH^- \rightarrow [M{\cdot}CO_2]_{ads} + H_2O + e^-$
8	$[M{\cdot}CO_2]_{ads} \rightarrow M + CO_2$

[a] Loss of protons from H1-N1-H2 amine group of urea.

[b] Loss of protons from H3-N2-H4 amine group of urea.

Table S2. Sum of free energies for all the intermediate steps (M=NiOOH).[1] Copyright (2010) American Chemical Society.

Reactions	ΔG/kJ mol^{-1}
$CO(NH_2)_2 + M \rightarrow [M{\cdot}CO(NH_2)_2]_{ads}$	66.2
$[M{\cdot}CO(NH_2)_2]_{ads} + OH^- \rightarrow [M{\cdot}CO(NH_2{\cdot}NH)]_{ads} + H_2O + 1e^-$	-28.9
$[M{\cdot}CO(NH_2{\cdot}NH)]_{ads} + OH^- \rightarrow [M{\cdot}CONH_2N]_{ads} + H_2O + 1e^-$	-185.1
$[M{\cdot}CO(NH_2N)]_{ads} + OH^- \rightarrow [M{\cdot}CONHN]_{ads} + H_2O + 1e^-$	75.4
$[M{\cdot}CONHN]_{ads} + OH^- \rightarrow [M{\cdot}CO{\cdot}N_2]_{ads} + H_2O + 1e^-$	-178.2
$[M{\cdot}CO{\cdot}N_2]_{ads} + OH^- \rightarrow [M{\cdot}CO{\cdot}OH]_{ads} + N_2 + 1e^-$	392.7
$[M{\cdot}CO{\cdot}OH]_{ads} + OH^- \rightarrow [M{\cdot}CO_2]_{ads} + H_2O + 1e^-$	-156.6
$[M{\cdot}CO_2]_{ads} \rightarrow M + CO_2$	1242.2
Total	1227.7

Table S3. The catalytic properties of Ni-based catalysts for UOR

Catalyst	Electrolyte	Scan rate /mV s^{-1}	Onset potential	Peak current density / mA cm^{-2}	Potential at 10 mA cm^{-2}/V	Ref.
Part A: Monometallic Ni catalyst						
ERGO-Ni	1 M KOH+0.33 M urea	10	-	35@0.7 vs. Hg/HgO	-	2
Ni decorated graphene	1 M KOH+2 M urea	50	-	150@0.8 V vs. Ag/AgCl	-	3
Gr/Ni	1 M KOH+0.33 M urea	50	0.38 V vs. Ag/AgCl	81.65@0.9 V vs. Ag/AgCl	-	4
Ni-WC/MWCNT	1 M KOH+0.33 M urea	10	-	46.6@0.7 vs. Hg/HgO	-	5
Ni-MOF(BTC)/CP	1 M KOH+1 M urea	5	1.34 V vs. RHE	63.15@1.5 V vs. RHE	-	6
Ni-MOF	1 M KOH+0.33 M urea	10	-	120@1.6 V vs. RHE	1.36 V vs. RHE	7
Ni-MOF-0.5	1 M KOH+0.5 M urea	5	-	-	1.381 V vs. RHE	8
Ni@carbon sponge	5 M NaOH+1 M urea	15	0.24 V vs. Ag/AgCl	290@0.47 V vs. Ag/AgCl	-	9
Part B: NiO catalyst						
NiO/NF	8 M NaOH+0.1 M urea	10	0.3 V vs. Ag/AgCl	222@0.48 V vs. Ag/AgCl	-	10
NiO/Gt	0.5 M NaOH+0.3 M urea	10	0.345 V vs. Ag/AgCl	17.63@0.64 V vs. Ag/AgCl	-	11
NiO-CFs	1 M KOH+1 M urea	25	-	61.06@0.45 V vs. Ag/AgCl	-	12
Ultrafine NiO	1 M KOH+0.25 M urea	20	-	15.34@0.45 V vs. Ag/AgCl	-	13
C@NiO	1 M KOH+0.33 M urea	-	-	25@1.46 V vs. RHE	1.36 V vs. RHE	14
Part C: $Ni(OH)_2$ catalyst						
$Ni(OH)_2$@NF	1 M KOH+0.33 M urea	5	-	-	1.35 V vs. RHE	15
$Ni(OH)_2$/Ni foam	5 M KOH+0.6 M urea	10	0.21 V vs. Ag/AgCl	337@0.45 V vs. Ag/AgCl	-	16
Porous $Ni(OH)_2$ nanosheets	1 M KOH+0.33 M urea	20	-	298@1.82 V vs. RHE	-	17
SL $Ni(OH)_2$ NS/CC	1 M KOH+0.33 M urea	10	-	436.4@0.5 V vs. Ag/AgCl	-	18

$Ni(OH)_2$-NSs/CC	1 M KOH+0.5 M urea	5	1.31 V vs. RHE	-	1.32 V vs. RHE	19
β-$Ni(OH)_2$-CNTs	1 M KOH+0.33 M urea	10	0.32 V vs. SCE	98.5@0.58 V vs. SCE	-	20
$Ni(OH)_2$ NS@NW/Ni foam	1 M KOH+0.33 M urea	5	-	-	0.34 V vs. SCE	21
Part D: Hetero-element doped Ni-based catalyst						
Rh-NCs/NiO-NSs	1 M KOH+0.33 M urea	50	-	52.05@1.5 V vs. RHE	-	22
NiIr-MOF/NF	1 M KOH+0.5 M urea	5	1.32 V vs. RHE	100@1.349 V vs. RHE	-	23
Fe: α-$Ni(OH)_2$/NF	1 M KOH+0.33 M urea	50	1.312 V vs. RHE	211.4@1.5 V vs. RHE	-	24
$Fe_{11.1\%}$–Ni_3S_2/Ni foam	1 M KOH+0.33 M urea	2	-	-	0.284 V vs. SCE	25
$Co_{0.26}$-$Ni(OH)_2$ NPs/CF	1 M KOH+0.5 M urea	5	1.27 V vs. RHE	-	1.38 V vs. RHE (at 100 mA cm^{-2})	26
NiCoPO	1 M KOH+0.1 M urea	100	0.22 V vs. Ag/AgCl	65.4@0.6 V vs. Ag/AgCl	-	27
Mo-doped Ni_3S_2	1 M KOH+0.3 M urea	2	-	-	1.33 V vs. RHE	28
Mn-Ni_3S_2/NF-0.2	1 M KOH+0.5 M urea	1	-	-	1.303 V vs. RHE	29
1% Ce:α-$Ni(OH)_2$/NF	1 M KOH+0.33 M urea	50	1.294 V vs. RHE	579.5@1.8 V vs. RHE	-	30
V–Ni_3N/NF	1 M KOH+0.5 M urea	2	-	-	1.361 V vs. RHE	31
Ni@NCNT-3	1 M KOH+0.5 M urea	-	-	45.8@1.5 V vs. RHE	1.38 V vs. RHE	32
Ni/SiOx/N-C	1 M KOH+0.33 M urea	5	-	-	1.384 V vs. RHE	33
NiFe/N–C	1 M KOH+1 M urea	5	-	100@1.37 V vs. RHE	1.37 V vs. RHE (at 100 mA cm^{-2})	34
$Ni(OH)_2$/F-doped Ni_3S_2	1 M KOH+0.33 M urea	50	-	322.9@1.7 V vs. RHE	-	35
Part E: Hetero-metallic alloy Ni-based catalyst (i) Metal alloy						
$Ni_{90}Pt_{10}$/C	1 M KOH+0.33 M urea	20	0.35 V vs. Hg/HgO	-	-	36
$Ni_{(10\%)}Pd_{(10\%)}$/OMC	1 M KOH+0.33 M urea	5	1.33 V vs. RHE	-	1.346 V vs. RHE (at 30 mA cm^{-2})	37

$Ni_{91}Rh_9$/C	1 M KOH+0.1 M urea	10	-	184@0.5 V vs. SCE	-	[38]
Ni-Rh/Ni foam	1 M KOH+0.05 M urea	10	0.33 V vs. Ag/AgCl	131.9@0.53 V vs. Ag/AgCl	-	[39]
NiFe hollow cages	1 M KOH+0.5 M urea	5	-	100@1.40 V vs. RHE	1.37 V vs. RHE	[40]
NP-$Ni_{0.7}Fe_{0.3}$ Ni foam	1 M KOH+0.33 M urea	5	-	-	1.33 V vs. RHE	[41]
Ni-Co alloy nanowire arrays	1 M KOH+0.33 M urea	10	0.372 V vs. Hg/HgO	322.82@0.65 vs. Hg/HgO	-	[42]
NiCo MOF/NF	1 M KOH+0.33 M urea	-	-	-	1.28 V vs. RHE	[43]
Ni_2Mo_1/G	1 M KOH+0.33 M urea	10	0.39 V vs. Ag/AgCl	128@0.53 V vs. Ag/AgCl	-	[44]
Ni-Mo nanotube	1 M KOH+0.1 M urea	5	-	-	1.36 V vs. RHE	[45]
Ni/Sn dendrites	1 M KOH+0.33 M urea	10	0.34 V vs. Ag/AgCl	44@0.55 V vs. Ag/AgCl	-	[46]
NiFeMo	1 M KOH+0.33 M urea	5	-	152@1.5 V vs. RHE	1.38 V vs. RHE	[47]
NiCoMo/graphene	1 M KOH+0.33 M urea	1	0.3 V vs. Ag/AgCl	69.8@0.55 V vs. Ag/AgCl	1.32 V vs. RHE	[48]
(ii) Nonmetal alloy						
Ni_3N/rGO@NF-350	1 M KOH+0.5 M urea	5	-	-	1.342 V vs. RHE	[49]
Ni_3N/NF	1 M KOH+0.5 M urea	-	-	-	1.34 V vs. RHE	[50]
Ni_3N-350/NF	1 M KOH+0.5 M urea	5	-	-	1.34 V vs. RHE	[51]
Ni_3N NA/CC	1 M KOH+0.33 M urea	5	-	-	1.35 V vs. RHE	[52]
Ni_2P-C	1 M KOH+0.33 M urea	10	-	70.4@0.5 V vs. SCE	-	[53]
a-Ni_2P/G	1 M KOH+0.5 M urea	5	-	209.1@1.7 V vs. RHE	1.28 V vs. RHE	[54]
P-NF	1 M KOH+0.33 M urea	5	-	-	1.32 V vs. RHE	[55]
Ni-P	1 M KOH+0.33 M urea	10	1.37 V vs. RHE	70@1.5 V vs. RHE	-	[56]
Ni_2P NF/CC	1 M KOH+0.5 M urea	5	-	-	0.447 V vs. SCE (at 100 mA cm^{-2})	[57]
Ni_3S_2/MWCNTs/NF	1 M KOH+0.5 M urea	5	-	-	1.338 V vs. RHE	[58]
β-NiS	1 M KOH+0.33 M urea	5	-	-	1.4 V vs. RHE	[59]
Ni_3S_2@NF	1 M NaOH+0.33 M urea	5	-	-	0.36 V vs. SCE	[60]

					(at 100 mA cm^{-2})	
Ni_3Se_4	1 M KOH+0.1 M urea	5	-	-	1.38 V vs. RHE	61
$Ni_{0.85}Se$/rGO	1 M KOH+0.5 M urea	5	-	-	1.36 V vs. RHE	62
$NiSe_2$	1 M KOH+0.33 M urea	5	-	-	1.36 V vs. RHE	63
Part F: Multi-component heterostructure Ni-based catalyst						
Ni/NiO@NC	1 M KOH+0.33 M urea	5	-	-	1.35 V vs. RHE	64
Ni/NiO-N-C-500	1 M KOH+0.33 M urea	10	1.38 V vs. RHE	117.9@1.56 V vs. RHE	-	65
Ni-NiO/Gr	1 M KOH+0.33 M urea	10	-	38.24@0.5 V vs. SCE	-	66
Ni@C-V_2O_3/NF	1 M KOH+0.5 M urea	5	-	-	1.32 V vs. RHE	67
(Ni-WO_2)@C/NF	1 M KOH+0.5 M urea	-	1.30 V vs. RHE	-	1.31 V vs. RHE	68
Ni_3S_2/Ni/NF	1 M KOH+0.5 M urea	-	-	-	1.30 V vs. RHE	69
Ni-Ni_3P@NPC/rGO	1 M KOH+0.5 M urea	5	-	-	1.38V vs. RHE (at 50 mA cm^{-2})	70
$NiSe_2$-NiO 350	1 M KOH+0.33 M urea	10	1.315 V vs. RHE		1.33 V vs. RHE	71
NiO/$NiCr_2O_4$	1 M KOH+0.33 M urea	5	-	49.7@0.5 V vs. Ag/AgCl	-	72
NiO-Fe_2O_3/rGO/PVA	1 M KOH+0.33 M urea	20	-	44.6@0.5 V vs. Ag/AgCl	-	73
CoN/$Ni(OH)_2$	1 M KOH+0.5 M urea	5	-	-	1.33 V vs. RHE (at 50 mA cm^{-2})	74
$Ni(OH)_2$-NiS-CC	1 M NaOH+0.05 M urea	10	0.31 V vs. Ag/AgCl	87.5@0.8 V vs. Ag/AgCl	-	75
$NiTe_2$/$Ni(OH)_2$/CFC	1 M KOH+0.33 M urea	2	1.355 V vs. RHE	73@1.523 V vs. RHE	-	76
Ni_4N/Cu_3N	1 M KOH+0.5 M urea	5	-	-	1.34 V vs. RHE	77
NiF_2/Ni_2P	1 M KOH+0.33 M urea	10	1.32 V vs. RHE	157.35@1.53 V vs. RHE	-	78
NiF_3/Ni_2P@CC-2	1 M KOH+0.33 M urea	10	1.33 V vs. RHE	122@1.6 V vs. RHE	1.36 V vs. RHE	79
Ni_2P/Fe_2P/NF	1 M KOH+0.5 M urea	10	-	-	1.36 V vs. RHE	80
MNPBA-P	1 M KOH+0.5 M urea	20	-	-	1.344 V vs. RHE	81

$Ni_{12}P_5$/Ni-Pi/NF	1 M KOH+0.5 M urea	5	-	900@1.378 V vs. RHE	-	82
N-NiS/NiS_2	1 M KOH+0.33 M urea	10	-	-	1.47 V vs. RHE (at 100 mA cm^{-2})	83
NiS/MoS_2@FCP	1 M KOH+0.4 M urea	5	-	-	1.42 V vs. RHE (at 50 mA cm^{-2})	84
NiS_2-MoS_2	1 M KOH+0.33 M urea	10	1.33 V vs. RHE	103.41@1.54 V vs. RHE	-	85
Cu_2S@Ni_3Se_2	1 M KOH+0.5 M urea	5	-	-	1.338 V vs. RHE	86
NiS@Ni_3S_2/$NiMoO_4$	1 M KOH+0.5 M urea	2	-	-	1.30 V vs. RHE	87
$MoNi_4$/MoOx@NF	1 M KOH+0.33 M urea	10	-	-	1.29 V vs. RHE	88
$FeNi_3$-MoO_2	1 M KOH+0.5 M urea	-	-	-	1.29 V vs. RHE	89
Ni-NiO-$Mo_{0.84}Ni_{0.16}$/NF	1 M KOH+0.5 M urea	5	1.29 V vs. RHE	-	1.33 V vs. RHE (at 50 mA cm^{-2})	90
Ni/$Ni_{0.2}Mo_{0.8}N$/MoO_3	1 M KOH+0.5 M urea	2	-	-	1.349 V vs. RHE	91

References

1. D. A. Daramola, D. Singh and G. G. Botte, *J. Phys. Chem. A*, 2010, **114**, 11513-11521.
2. D. Wang, W. Yan, S. H. Vijapur and G. G. Botte, *Electrochim. Acta*, 2013, **89**, 732-736.
3. N. A. M. Barakat, M. Motlak, Z. K. Ghouri, A. S. Yasin, M. H. El-Newehy and S. S. Al-Deyab, *J. Mol. Catal. A: Chem*, 2016, **421**, 83-91.
4. A. Yousef, M. H. El-Newehy, S. S. Al-Deyab and N. A. M. Barakat, *Arab. J. Chem.*, 2017, **10**, 811-822.
5. L. Wang, T. Du, J. Cheng, X. Xie, B. Yang and M. Li, *J. Power. Sources*, 2015, **280**, 550-554.
6. V. Maruthapandian, S. Kumaraguru, S. Mohan, V. Saraswathy and S. Muralidharan, *ChemElectroChem*, 2018, **5**, 2795-2807.
7. D. Zhu, C. Guo, J. Liu, L. Wang, Y. Du and S.-Z. Qiao, *Chem. Commun.*, 2017, **53**, 10906-10909.
8. S. Zheng, Y. Zheng, H. Xue and H. Pang, *Chem. Eng. J.*, 2020, **395**, 125166.
9. K. Ye, D. Zhang, F. Guo, K. Cheng, G. Wang and D. Cao, *J. Power. Sources*, 2015, **283**, 408-415.
10. D. Zhang, J. Zhang, H. Wang, C. Cui, W. Jiao, J. Gao and Y. Liu, *J. Alloy. Compd.*, 2019, **806**, 1419-1429.
11. R. M. Abdel Hameed and S. S. Medany, *Int. J. Hydrogen. Energ.*, 2017, **42**, 24117-24130.
12. H. M. Abd El-Lateef, M. M. Khalaf and I. M. A. Mohamed, *Ceram. Int.*, 2020, **46**, 20376-20384.
13. H. M. Abd El-Lateef, N. F. Almulhim, A. A. Alaulamie, M. M. Saleh and I. M. A. Mohamed, *Colloid Surface A*, 2020, **585**, 124092.
14. S. Lu, M. Hummel, Z. Gu, Y. Wang, K. Wang, R. Pathak, Y. Zhou, H. Jia, X. Qi, X. Zhao, B. B. Xu and X. Liu, *ACS Sustain. Chem. Eng.*, 2021, **9**, 1703-1713.
15. L. Xia, Y. Liao, Y. Qing, H. Xu, Z. Gao, W. Li and Y. Wu, *ACS Appl. Energ. Mater.*, 2020, **3**, 2996-3004.
16. K. Ye, H. Zhang, L. Zhao, X. Huang, K. Cheng, G. Wang and D. Cao, *New J. Chem.*, 2016, **40**, 8673-8680.
17. W. Yang, X. Yang, B. Li, J. Lin, H. Gao, C. Hou and X. Luo, *J. Mater. Chem. A*, 2019, **7**, 26364-26370.
18. C. Lin, Z. Gao, F. Zhang, J. Yang, B. Liu and J. Jin, *J. Mater. Chem. A*, 2018, **6**, 13867-13873.
19. J. Chen, S. Ci, G. Wang, N. Senthilkumar, M. Zhang, Q. Xu and Z. Wen, *ChemElectroChem*, 2019, **6**, 5313-5320.
20. Q. Gan, X. Cheng, J. Chen, D. Wang, B. Wang, J. Tian, T. T. Isimjan and X. Yang, *Electrochim. Acta*, 2019, **301**, 47-54.
21. Z. Yue, S. Yao, Y. Li, W. Zhu, W. Zhang, R. Wang, J. Wang, L. Huang, D. Zhao and J. Wang, *Electrochim. Acta*, 2018, **268**, 211-217.
22. G. Ma, Q. Xue, J. Zhu, X. Zhang, X. Wang, H. Yao, G. Zhou and Y. Chen, *Appl. Catal. B.*, 2020, **265**, 118567.
23. Y. Xu, X. Chai, T. Ren, S. Yu, H. Yu, Z. Wang, X. Li, L. Wang and H. Wang, *Chem. Commun.*, 2020, **56**, 2151-2154.
24. J. Xie, W. Liu, F. Lei, X. Zhang, H. Qu, L. Gao, P. Hao, B. Tang and Y. Xie, *Chem. Eur. J.*, 2018, **24**, 18408-18412.
25. W. Zhu, Z. Yue, W. Zhang, N. Hu, Z. Luo, M. Ren, Z. Xu, Z. Wei, Y. Suo and J. Wang, *J. Mater. Chem. A*, 2018, **6**, 4346-4353.
26. C. B. Sun, M. W. Guo, S. S. Siwal and Q. B. Zhang, *J. Catal.*, 2020, **381**, 454-461.

27. J.-H. Yang, X. Song, X. Zhao, Y. Wang, Y. Yang and L. Gao, *Int. J. Hydrogen. Energ.*, 2019, **44**, 16305-16314.
28. H. Xu, Y. Liao, Z. Gao, Y. Qing, Y. Wu and L. Xia, *J. Mater. Chem. A*, 2021, **9**, 3418-3426.
29. H. Yang, M. Yuan, Z. Sun, D. Wang, L. Lin, H. Li and G. Sun, *ACS Sustain. Chem. Eng.*, 2020, **8**, 8348-8355.
30. J. Xie, W. Liu, X. Zhang, Y. Guo, L. Gao, F. Lei, B. Tang and Y. Xie, *ACS Mater. Lett.*, 2019, **1**, 103-110.
31. R.-Q. Li, Q. Liu, Y. Zhou, M. Lu, J. Hou, K. Qu, Y. Zhu and O. Fontaine, *J. Mater. Chem. A*, 2021, **9**, 4159-4166.
32. Q. Zhang, F. M. D. Kazim, S. Ma, K. Qu, M. Li, Y. Wang, H. Hu, W. Cai and Z. Yang, *Appl. Catal. B.*, 2021, **280**, 119436.
33. M. Yuan, X. Guo, N. Li and H. Pang, *J. Colloid Interf. Sci.*, 2021, **589**, 56-64.
34. J. Zhang, F. Xing, H. Zhang and Y. Huang, *Dalton T.*, 2020, **49**, 13962-13969.
35. P. Hao, W. Zhu, F. Lei, X. Ma, J. Xie, H. Tan, L. Li, H. Liu and B. Tang, *Nanoscale*, 2018, **10**, 20384-20392.
36. J. R. Barbosa, C. H. Paranhos, O. C. Alves, N. R. Checca, J. P. Serna, A. L. Rossi and J. C. M. Silva, *Electrochim. Acta*, 2020, **355**, 136752.
37. N. Muthuchamy, S. Jang, J. C. Park, S. Park and K. H. Park, *ACS Sustain. Chem. Eng.*, 2019, **7**, 15526-15536.
38. P. Mirzaei, S. Bastide, A. Dassy, R. Bensimon, J. Bourgon, A. Aghajani, C. Zlotea, D. Muller-Bouvet and C. Cachet-Vivier, *Electrochim. Acta*, 2019, **297**, 715-724.
39. S. Qian, Z. Rao, Y. Liu, J. Yan, B. Fan, Y. Gui and F. Guo, *Electrochim. Acta*, 2020, **330**, 135211.
40. Y. Feng, X. Wang, P. Dong, J. Li, L. Feng, J. Huang, L. Cao, L. Feng, K. Kajiyoshi and C. Wang, *Sci. Rep.*, 2019, **9**, 15965.
41. Z. Cao, T. Zhou, X. Ma, Y. Shen, Q. Deng, W. Zhang and Y. Zhao, *ACS Sustain. Chem. Eng.*, 2020, **8**, 11007-11015.
42. X. Gao, Y. Wang, W. Li, F. Li, H. Arandiyan, H. Sun and Y. Chen, *Electrochim. Acta*, 2018, **283**, 1277-1283.
43. D. Wei, W. Tang, N. Ma and Y. Wang, *J. Alloy. Compd.*, 2021, **874**, 159945.
44. W. Shi, R. Ding, X. Li, Q. Xu and E. Liu, *Electrochim. Acta*, 2017, **242**, 247-259.
45. J.-Y. Zhang, T. He, M. Wang, R. Qi, Y. Yan, Z. Dong, H. Liu, H. Wang and B. Y. Xia, *Nano Energy*, 2019, **60**, 894-902.
46. R. K. Singh, P. Subramanian and A. Schechter, *ChemElectroChem*, 2017, **4**, 1037-1043.
47. Z. Lv, Z. Li, X. Tan, Z. Li, R. Wang, M. Wen, X. Liu, G. Wang, G. Xie and L. Jiang, *Appl. Surf. Sci.*, 2021, **552**, 149514.
48. W. Shi, X. Sun, R. Ding, D. Ying, Y. Huang, Y. Huang, C. Tan, Z. Jia and E. Liu, *Chem. Commun.*, 2020, **56**, 6503-6506.
49. F. Wang, D. Zhao, L. Zhang, L. Fan, X. Zhang and S. Hu, *Nanomaterials (Basel)*, 2019, **9**, 1583.
50. S. Hu, C. Feng, S. Wang, J. Liu, H. Wu, L. Zhang and J. Zhang, *ACS Appl. Mater. Interfaces*, 2019, **11**, 13168-13175.
51. Z. Zhao, J. Zhao, H. Wang, X. Li, L. Yang, Z. Zhao, X. Liu, Y. Liu, P. Liu and Z. Cai, *Int. J. Hydrogen. Energ.*, 2020, **45**, 14199-14207.
52. Q. Liu, L. Xie, F. Qu, Z. Liu, G. Du, A. M. Asiri and X. Sun, *Inorg. Chem. Front.*, 2017, **4**, 1120-1124.

53. D. Yang, Y. Gu, X. Yu, Z. Lin, H. Xue and L. Feng, *ChemElectroChem*, 2018, **5**, 659-664.
54. Y. Tong, L. Chen, P. J. Dyson and Z. Fei, *J. Mater. Sci.*, 2021, **56**, 17709-17720.
55. L. Fei, H. Sun, R. Ran, W. Zhou and Z. Shao, *Ind. Eng. Chem. Res.*, 2021, **60**, 1185-1193.
56. R. Ding, X. Li, W. Shi, Q. Xu, L. Wang, H. Jiang, Z. Yang and E. Liu, *Electrochim. Acta*, 2016, **222**, 455-462.
57. D. Liu, T. Liu, L. Zhang, F. Qu, G. Du, A. M. Asiri and X. Sun, *J. Mater. Chem. A*, 2017, **5**, 3208-3213.
58. Z. Zhao, L. Yang, Z. Wang, L. Wang, G. Guo, J. Chen, Y. Li, C. Wang, J. Zhao and Z. Cai, *J. Electrochem. Soc.*, 2020, **167**, 126514.
59. T.-H. Wu, Y.-C. Lin, B.-W. Hou and W.-Y. Liang, *Catalysts*, 2020, **10**, 1280.
60. M. Liu, Y. Jiao, S. Zhan and H. Wang, *Catal. Today*, 2020, **355**, 596-601.
61. J.-Y. Zhang, X. Tian, T. He, S. Zaman, M. Miao, Y. Yan, K. Qi, Z. Dong, H. Liu and B. Y. Xia, *J. Mater. Chem. A*, 2018, **6**, 15653-15658.
62. L. Zhao, Y. Chang, M. Jia, J. Jia and Z. Wen, *J. Alloy. Compd.*, 2021, **852**, 156751.
63. P. Xiong, X. Ao, J. Chen, J.-G. Li, L. Lv, Z. Li, M. Zondode, X. Xue, Y. Lan and C. Wang, *Electrochim. Acta*, 2019, **297**, 833-841.
64. X. Ji, Y. Zhang, Z. Ma and Y. Qiu, *ChemSusChem*, 2020, **13**, 5004-5014.
65. N. Wu, R. Guo, X. Zhang, N. Gao, X. Chi, D. Cao and T. Hu, *J. Alloy. Compd.*, 2021, **870**, 159408.
66. S. Wang, P. Xu, J. Tian, Z. Liu and L. Feng, *Electrochim. Acta*, 2021, **370**, 137755.
67. G. Qian, J. Chen, L. Luo, H. Zhang, W. Chen, Z. Gao, S. Yin and P. Tsiakaras, *ACS Appl. Mater. Interfaces*, 2020, **12**, 38061-38069.
68. F. Shen, W. Jiang, G. Qian, W. Chen, H. Zhang, L. Luo and S. Yin, *J. Power. Sources*, 2020, **458**, 228014.
69. X. Zhuo, W. Jiang, G. Qian, J. Chen, T. Yu, L. Luo, L. Lu, Y. Chen and S. Yin, *ACS Appl. Mater. Interfaces*, 2021, **13**, 35709-35718.
70. G. Li, J. Wang, J. Yu, H. Liu, Q. Cao, J. Du, L. Zhao, J. Jia, H. Liu and W. Zhou, *Appl. Catal. B.*, 2020, **261**, 118147.
71. Z. Liu, C. Zhang, H. Liu and L. Feng, *Appl. Catal. B.*, 2020, **276**, 119165.
72. Y. Liu, M. Huang, J. Zhao, M. Lu, X. Zhou, Q. Lin, P. Wang and J. Zhu, *J. Electrochem. Soc.*, 2020, **167**, 066520.
73. G. Das, R. M. Tesfaye, Y. Won and H. H. Yoon, *Electrochim. Acta*, 2017, **237**, 171-176.
74. Y. Cheng, F. Liao, H. Dong, H. Wei, H. Geng and M. Shao, *J. Power. Sources*, 2020, **480**, 229151.
75. H. Wang, L. Zhang, H. Jiang, P. Kannan, R. Wang, P. Subramanian and S. Ji, *J. Alloy. Compd.*, 2021, **870**, 159486.
76. B. Xu, X. Yang, X. Liu, W. Song, Y. Sun, Q. Liu, H. Yang and C. Li, *J. Power. Sources*, 2020, **449**, 227585.
77. J. Li, C. Yao, X. Kong, Z. Li, M. Jiang, F. Zhang and X. Lei, *ACS Sustain. Chem. Eng.*, 2019, **7**, 13278-13285.
78. H. Liu, Z. Liu and L. Feng, *Nanoscale*, 2019, **11**, 16017-16025.
79. K. Wang, W. Huang, Q. Cao, Y. Zhao, X. Sun, R. Ding, W. Lin, E. Liu and P. Gao, *Chem. Eng. J.*, 2022, **427**, 130865.
80. L. Yan, Y. Sun, E. Hu, J. Ning, Y. Zhong, Z. Zhang and Y. Hu, *J. Colloid Interf. Sci.*, 2019, **541**, 279-286.
81. H. Xu, K. Ye, K. Zhu, Y. Gao, J. Yin, J. Yan, G. Wang and D. Cao, *ACS Sustain. Chem. Eng.*, 2020,

8, 16037-16045.
82. X. Xu, P. Du, T. Guo, B. Zhao, H. Wang and M. Huang, *ACS Sustain. Chem. Eng.*, 2020, **8**, 7463-7471.
83. H. Liu, Z. Liu, F. Wang and L. Feng, *Chem. Eng. J.*, 2020, **397**, 125507.
84. Y. Zheng, P. Tang, X. Xu and X. Sang, *J. Solid State Chem.*, 2020, **292**, 121644.
85. S. Wang, L. Zhao, J. Li, X. Tian, X. Wu and L. Feng, *J. Energy Chem.*, 2022, **66**, 483-492.
86. L. Lv, Z. Li, H. Wan and C. Wang, *J. Colloid Interf. Sci.*, 2021, **592**, 13-21.
87. L. Sha, T. Liu, K. Ye, K. Zhu, J. Yan, J. Yin, G. Wang and D. Cao, *J. Mater. Chem. A*, 2020, **8**, 18055-18063.
88. L. Meng, L. Li, J. Wang, S. Fu, Y. Zhang, J. Li, C. Xue, Y. Wei and G. Li, *Electrochim. Acta*, 2020, **350**, 136382.
89. Q. Xu, T. Yu, J. Chen, G. Qian, H. Song, L. Luo, Y. Chen, T. Liu, Y. Wang and S. Yin, *ACS Appl. Mater. Interfaces*, 2021, **13**, 16355-16363.
90. Q. Xu, G. Qian, S. Yin, C. Yu, W. Chen, T. Yu, L. Luo, Y. Xia and P. Tsiakaras, *ACS Sustain. Chem. Eng.*, 2020, **8**, 7174-7181.
91. R.-Q. Li, S. Li, M. Lu, Y. Shi, K. Qu and Y. Zhu, *J. Colloid Interf. Sci.*, 2020, **571**, 48-54.