Ultra-small RuO_2/NHC nanocrystal electrocatalysts with efficient water oxidation activities in acidic media

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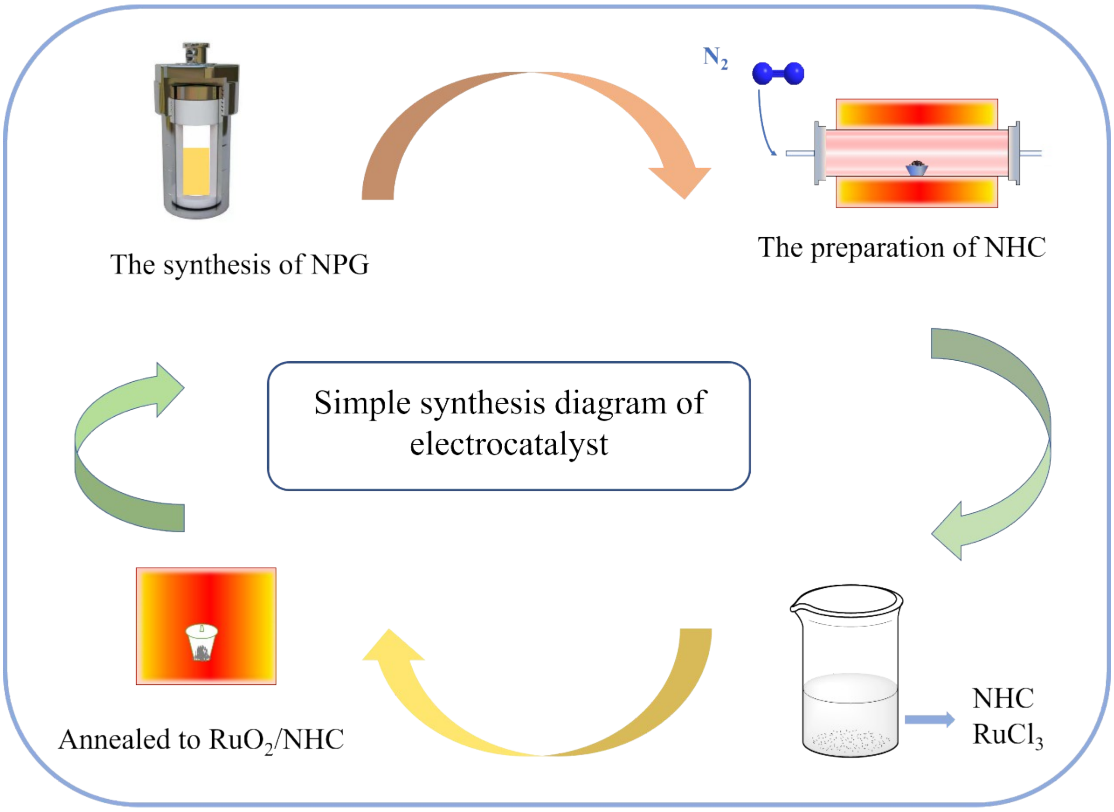


Fig S1. Simple synthesis flow diagram of electrocatalyst RuO_2/NHC.

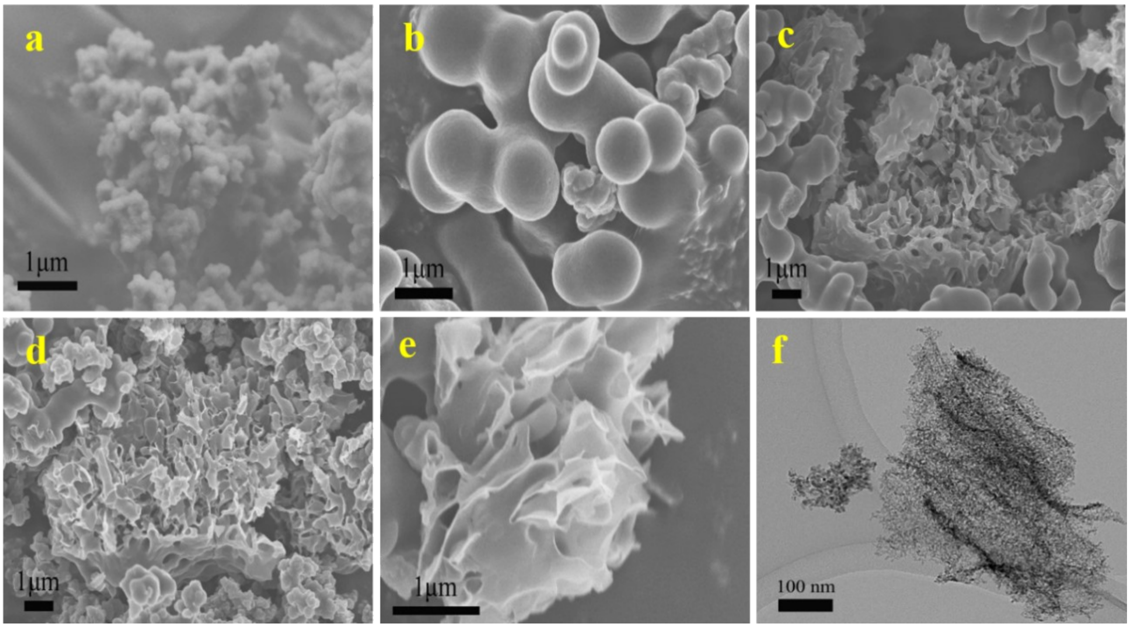


Fig S2. SEM of a) NPG; b) NHC^0; c) NHC^1; d) NHC^2; e) NHC^4 and f) TEM of RuO_2/NHC^3.

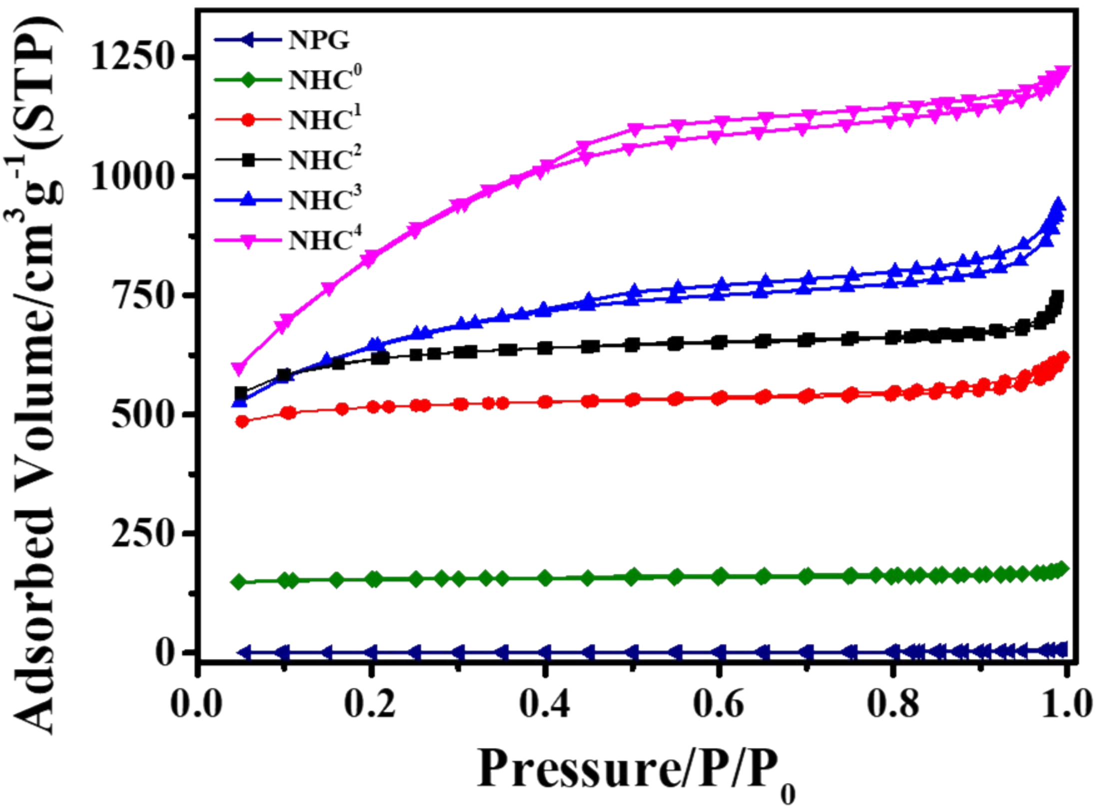


Fig S3. Nitrogen adsorption-desorption isotherms of different supporter samples.

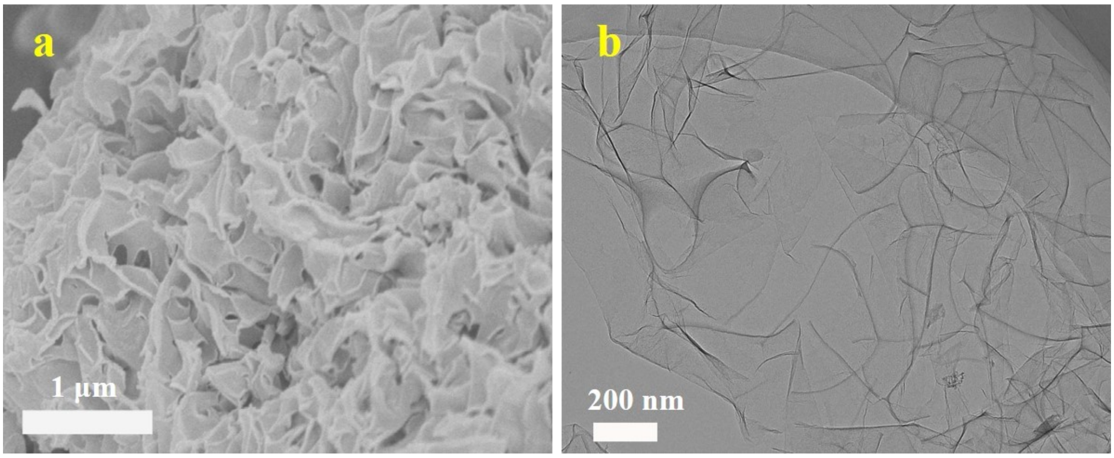


Fig S4. a) SEM of NHC^3 and b) TEM image of NHC^3.

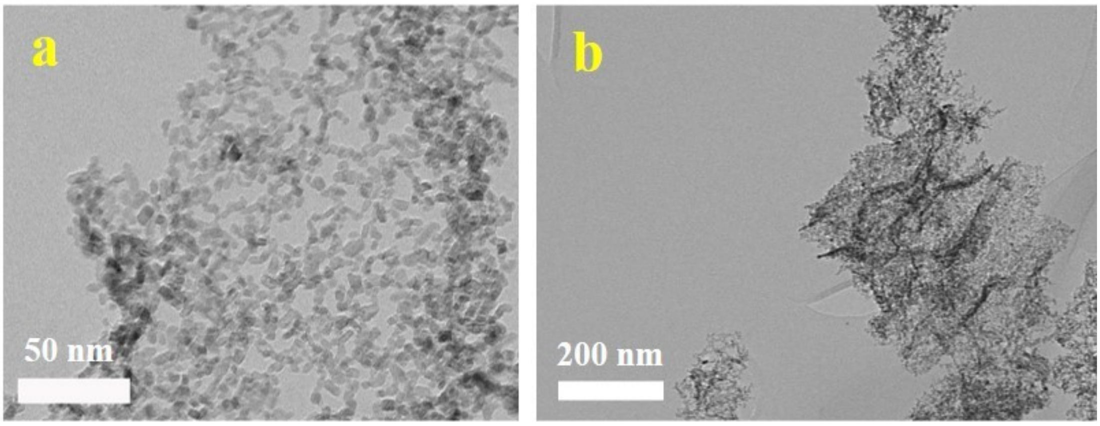


Fig S5. TEM of RuO_2/NHC[3] at different multiples.

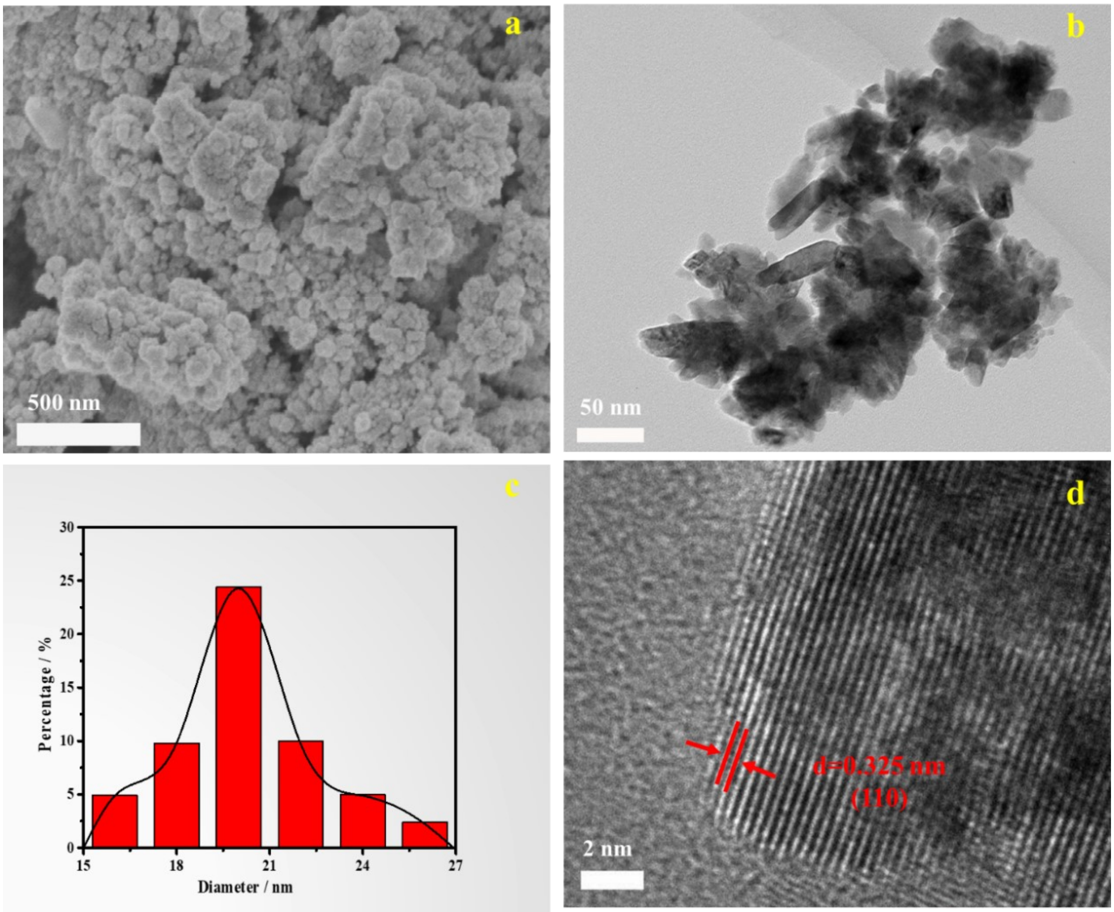


Fig S6. a) SEM of RuO_2; b) TEM image of RuO_2; c) particle size image of RuO_2 and d) HR-TEM image of RuO_2.

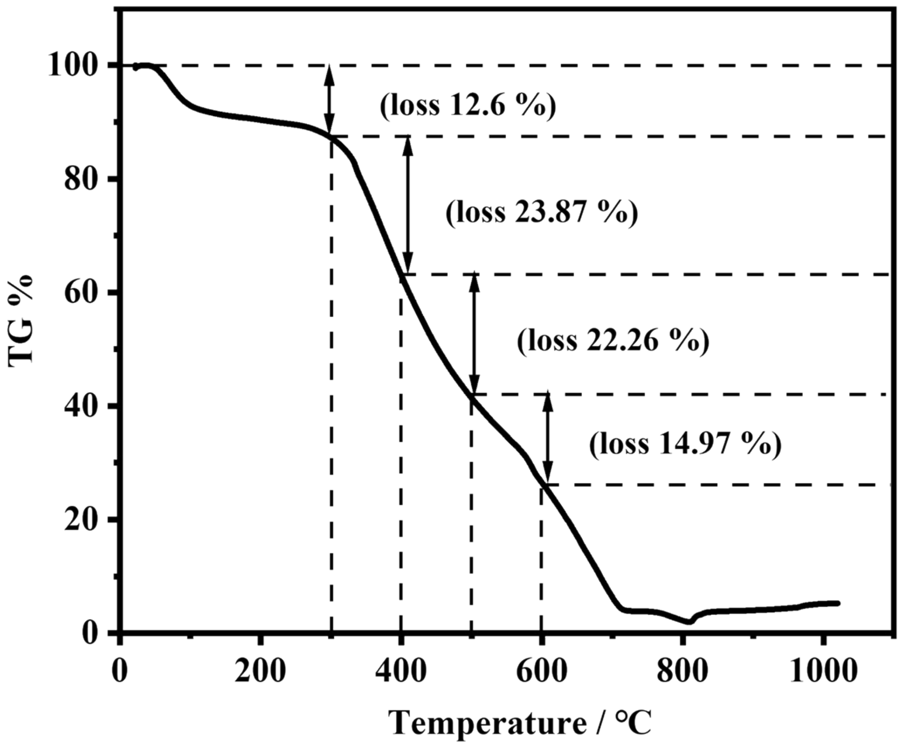


Fig S7. TGA plot of precursor of RuO_2/NHC in 20 mL/min air atmosphere with temperature ramping 10 °C/min.

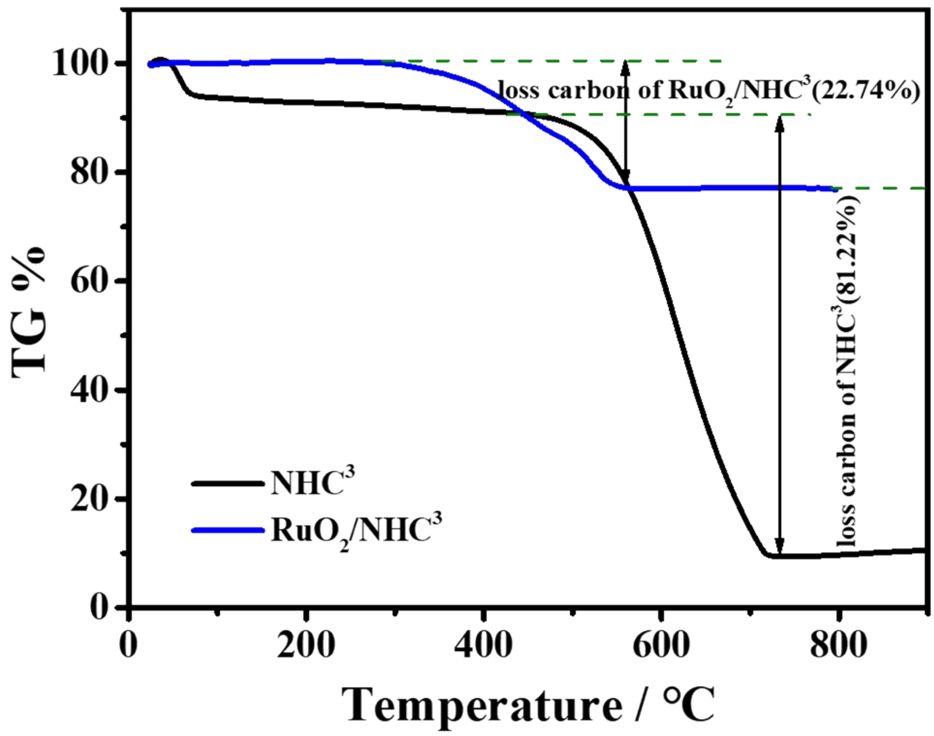


Fig S8. TGA plot of RuO_2/NHC^3 and NHC^3 in 20 mL/min air atmosphere with temperature ramping 10 °C/min.

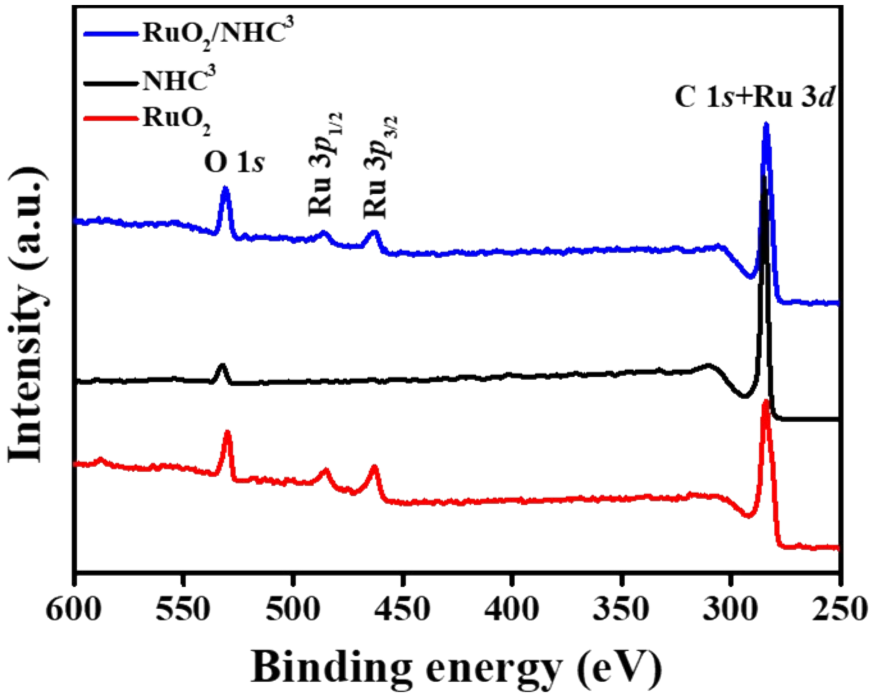


Fig S9. XPS survey spectra of NHC^3, RuO_2/NHC^3 and RuO_2 electrocatalysts.

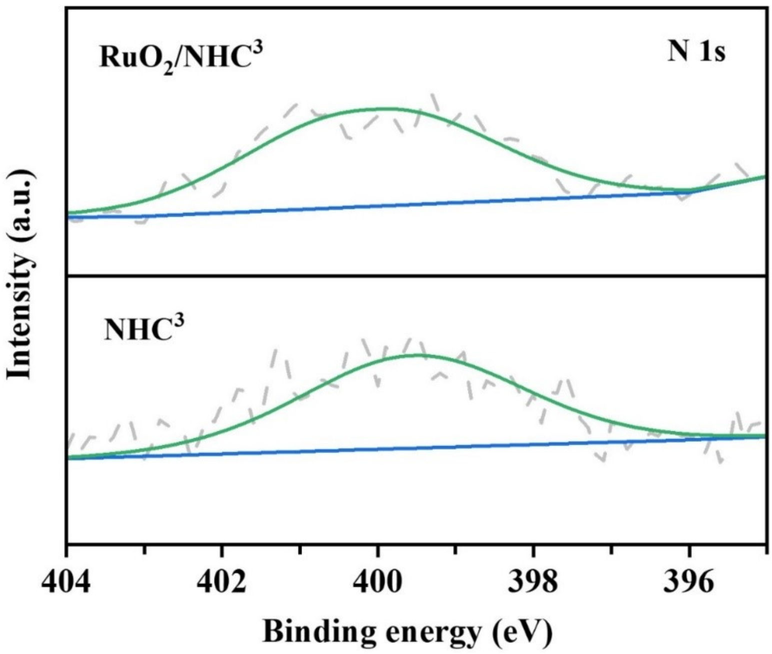
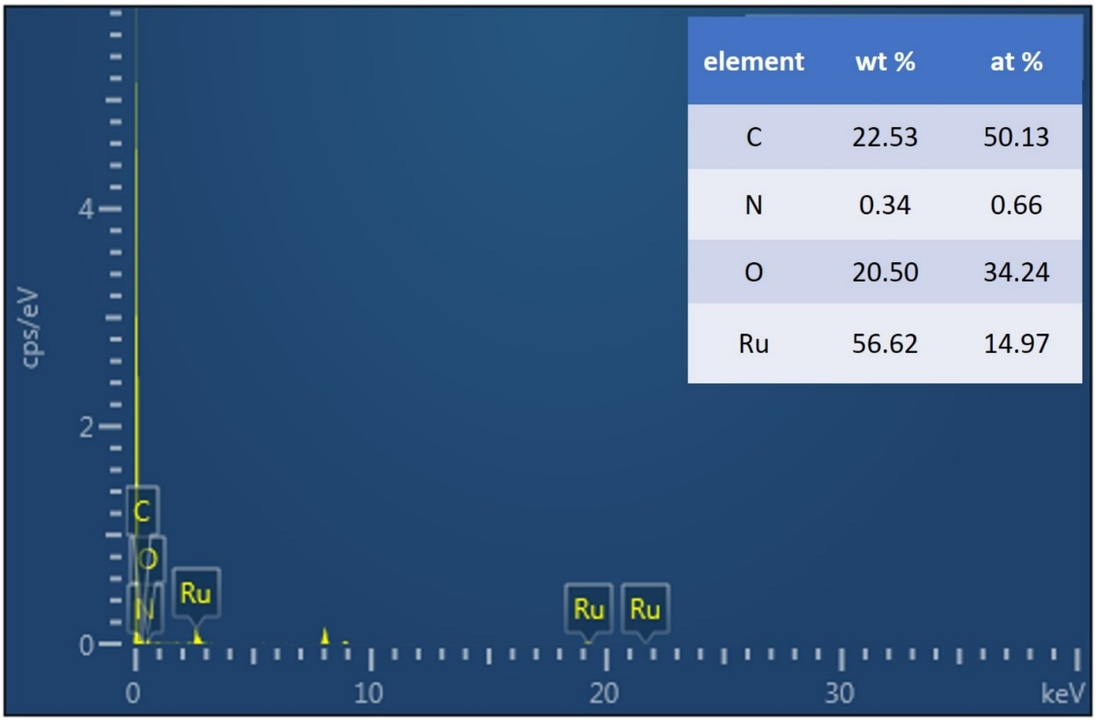


Fig S10. High resolution XPS spectra of N 1s of electrocatalysts RuO_2/NHC^3 and NHC^3.



element	wt %	at %
C	22.53	50.13
N	0.34	0.66
O	20.50	34.24
Ru	56.62	14.97

Fig S11. EDS analysis for RuO_2/NHC[3].

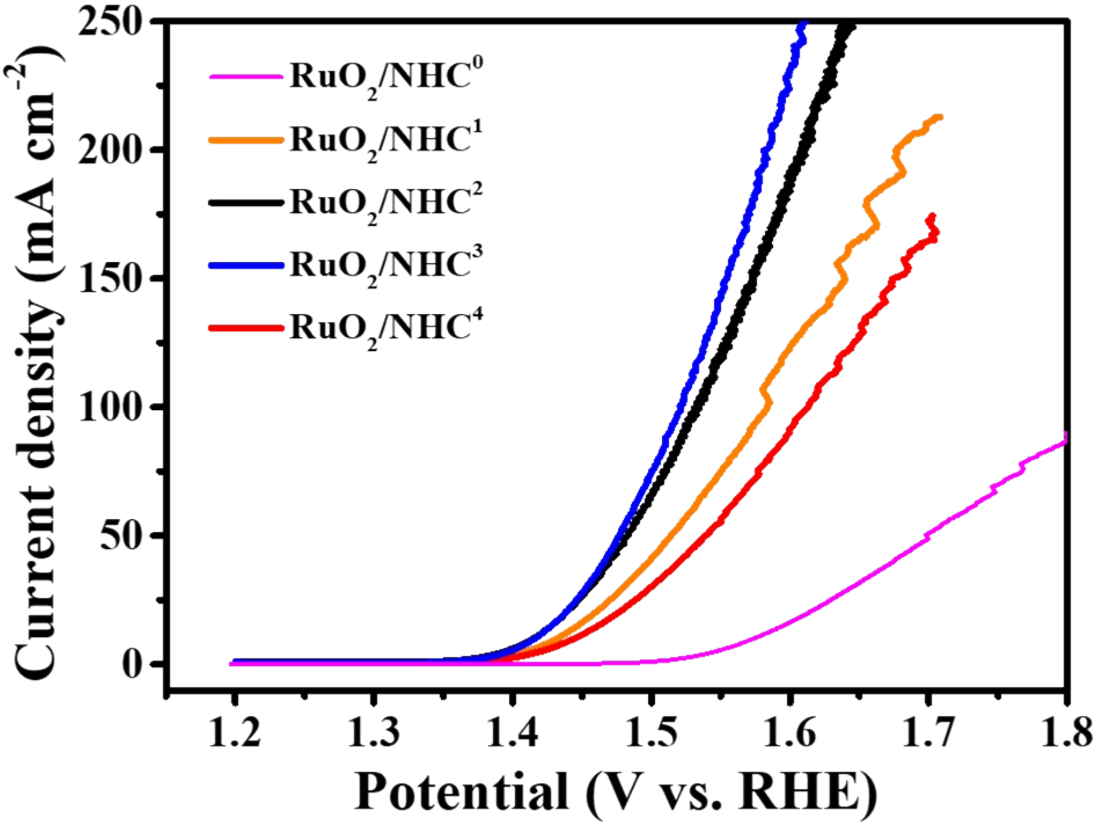


Fig S12. Polarization curves of RuO_2/NHC^0, RuO_2/NHC^1, RuO_2/NHC^2, RuO_2/NHC^3, RuO_2/NHC^4 in 0.5 M H_2SO_4.

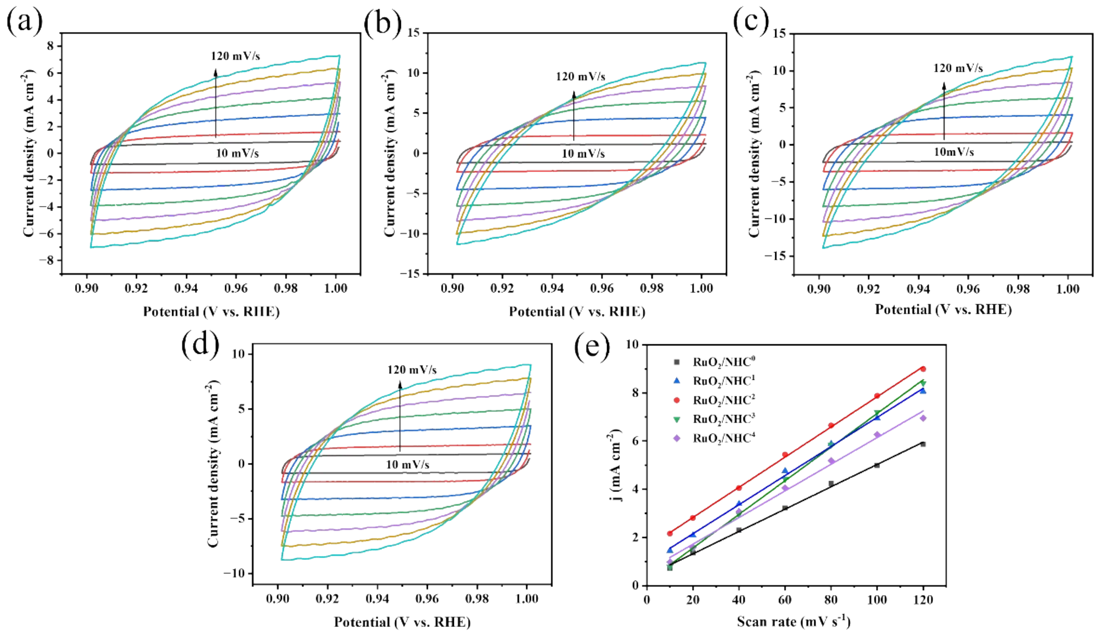


Fig S13. CV curves of a) RuO_2/NHC^0, b) RuO_2/NHC^1, c) RuO_2/NHC^2 and d) RuO_2/NHC^4 e) Current density as a function of the scan rate for different samples for OER.

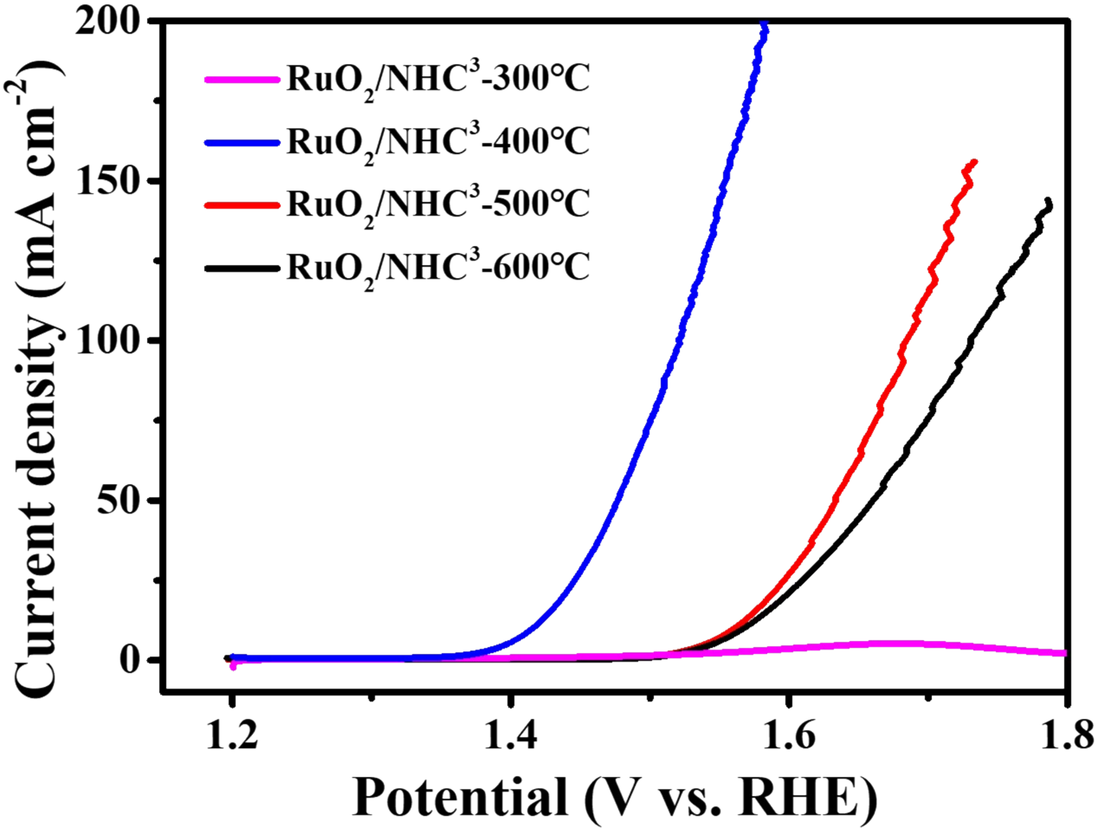


Fig S14. Polarization curves of RuO_2/NHC^3-300 °C, RuO_2/NHC^3-400 °C, RuO_2/NHC^3-500 °C, RuO_2/NHC^3-600 °C.

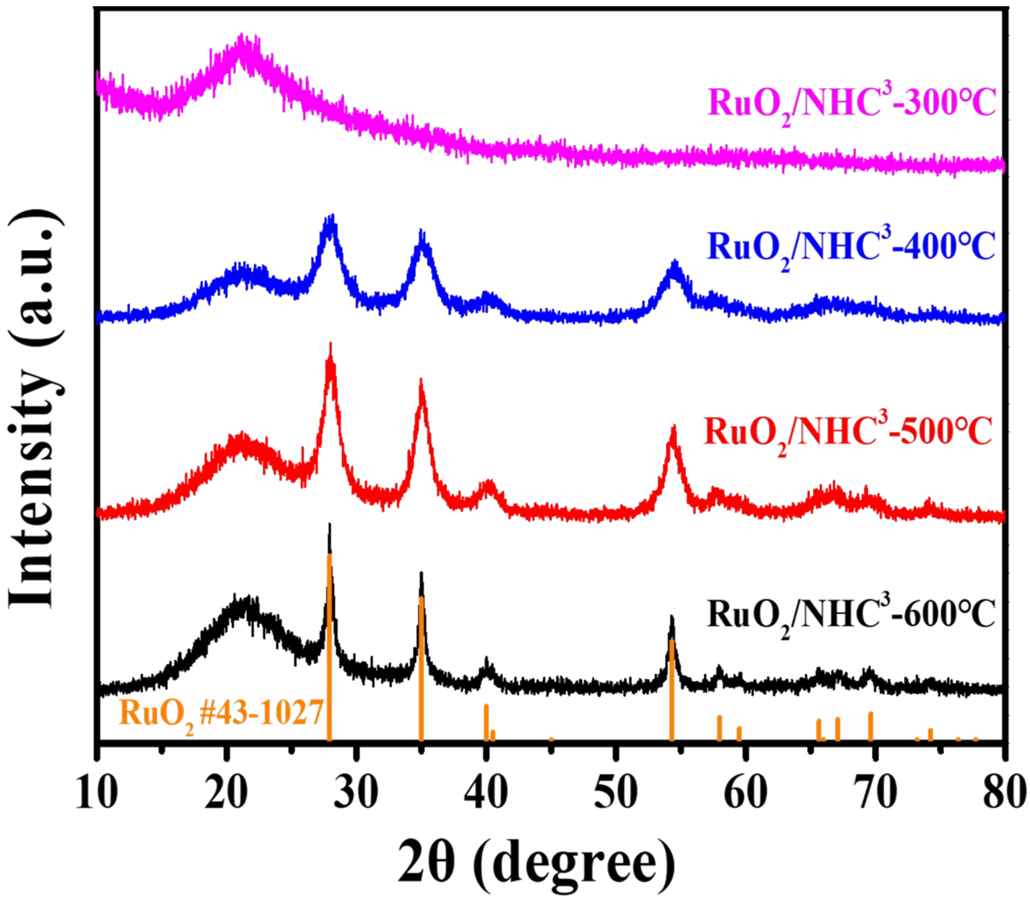


Fig S15. XRD pattern of RuO_2/NHC^3-300 °C, RuO_2/NHC^3-400 °C, RuO_2/NHC^3-500 °C, RuO_2/NHC^3-600 °C.

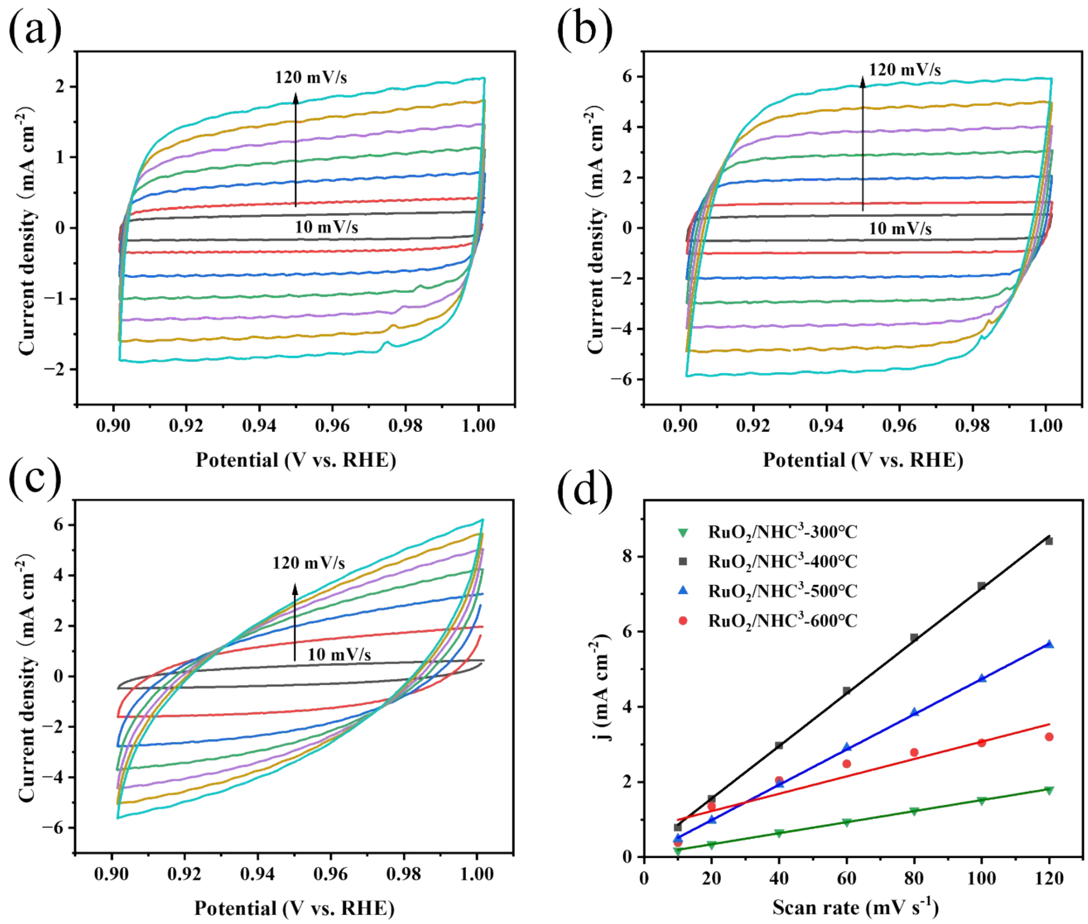


Fig S16. CV curves of a) RuO_2/NHC^3-300 °C, b) RuO_2/NHC^3-500 °C, c) RuO_2/NHC^3-600 °C and d) Current density as a function of the scan rate for different samples for OER.

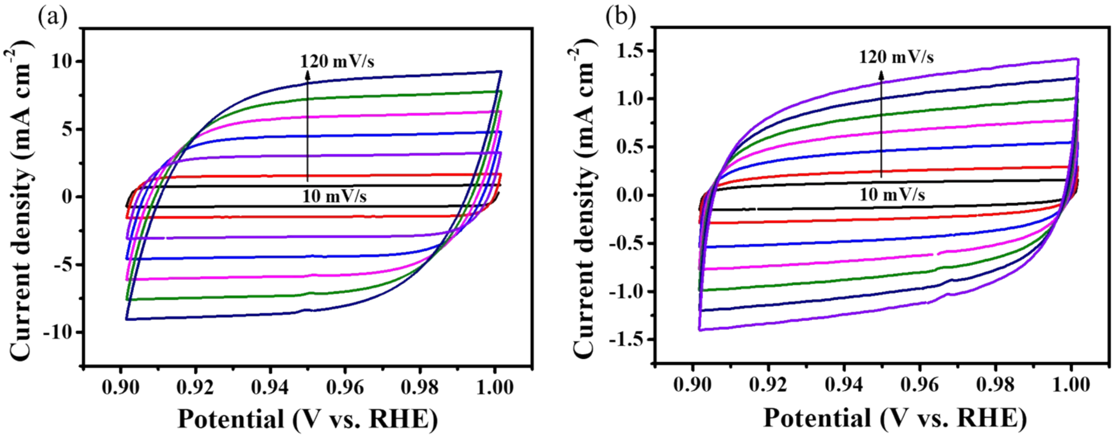


Fig S17. CVs measured at different scan rates from 10 to 120 mV/s of (a) RuO_2/NHC[3] and (b) RuO_2.

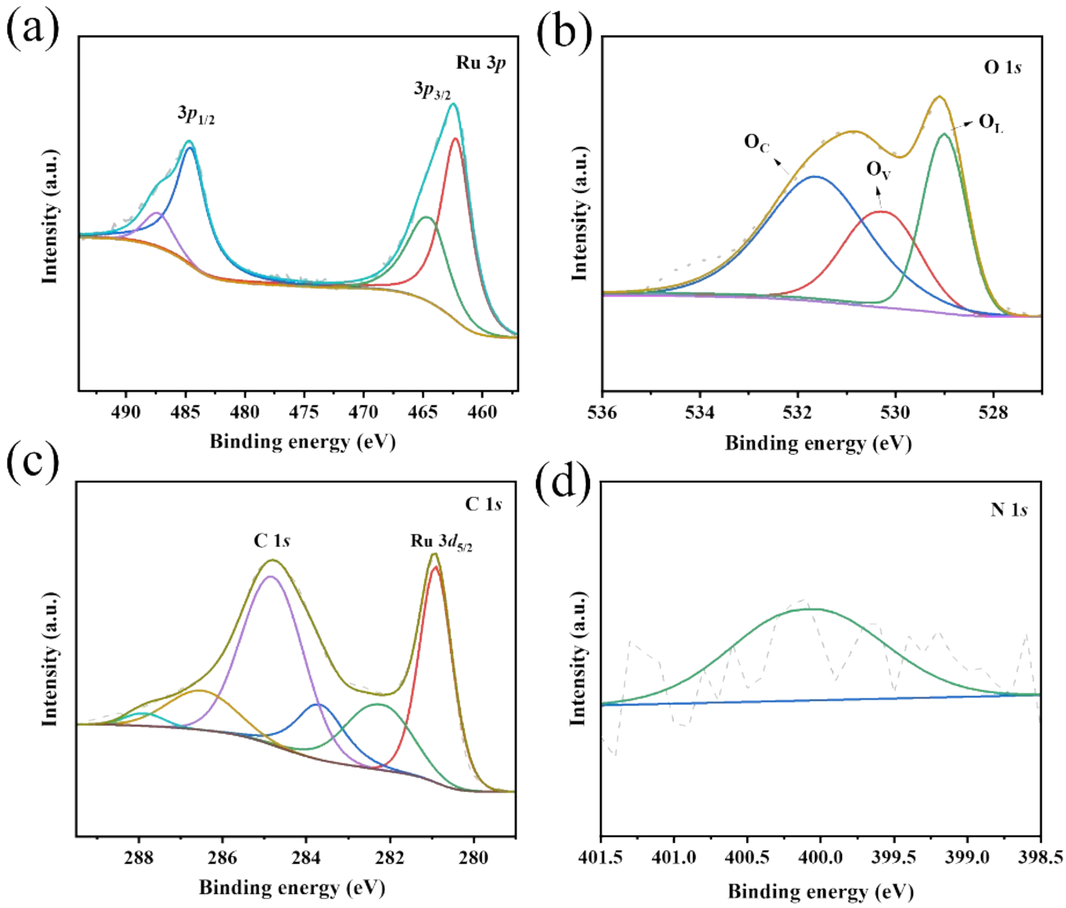


Fig S18. a) Ru 3p, b) O 1s, c) C1s and d) N 1s XPS spectra of RuO_2/NHC[3] after long time chronopotentiometry test.

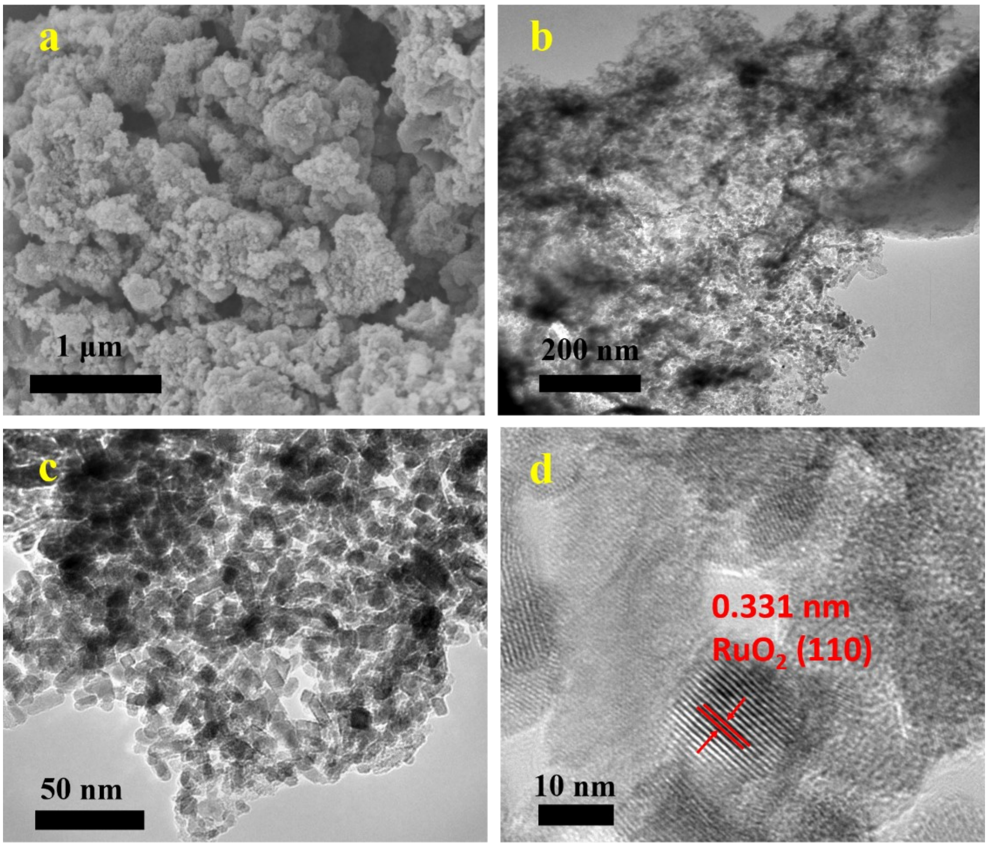


Fig S19. a) SEM, b-c) TEM image and d) HR-TEM image of RuO_2/NHC[3] after long time chronopotentiometry test.

Table S1. BET surface area and overpotential at 10 mA/cm^2 of various samples.

Sample	**S_{BET} (m^2/g)**	**Sample**	**η_{10} (mV)**
NPG	4	RuO_2/NPG	NA
NHC^0	468	RuO_2/NHC^0	344
NHC^1	1563	RuO_2/NHC^1	202
NHC^2	1894	RuO_2/NHC^2	185
NHC^3	**2107**	**RuO_2/NHC^3**	**186**
NHC^4	2998	RuO_2/NHC^4	215

Table S2. The C_{dl} and ECSA of RuO_2/NHC^0, RuO_2/NHC^1, RuO_2/NHC^2, RuO_2/NHC^3 and RuO_2/NHC^4 for OER.

Sample	**C_{dl} (mF/cm^2)**	**ECSA (cm^2/mg)**
RuO_2/NHC^0	46.3	1157.5
RuO_2/NHC^1	60.3	1507.5
RuO_2/NHC^2	62.6	1565
RuO_2/NHC^3	**69.8**	**1745**
RuO_2/NHC^4	55.3	1382.5

Table S3. The C_{dl} and ECSA of RuO_2/NHC[3]-300 °C, RuO_2/NHC[3]-400 °C, RuO_2/NHC[3]-500 °C and RuO_2/NHC[3]-600 °C for OER.

Sample	C_{dl} (mF/cm^2)	ECSA (cm^2/mg)
RuO_2/NHC[3]-300 °C	14.7	367.5
RuO_2/NHC[3]-400 °C	**69.8**	**1745**
RuO_2/NHC[3]-500 °C	46.9	1172.5
RuO_2/NHC[3]-600 °C	23.1	577.5

Table S4. Parameters of R_s and R_{ct} acquired through fitting EIS spectra.

electrocatalyst	R_s (ohm)	R_{ct} (ohm)
RuO_2/NHC[3]	**1.60**	**0.4189**
RuO_2	1.898	5.04
NHC[3]	19.98	1.716

Table S5. Comparison of the Ru-based electrocatalysts reported in representative literature under acidic electrolyte.

Catalysts	Electrolyte	η(mV) at 10 mA/cm^2	Stability	Ref
RuO_2/NHC[3]	**0.5 M H_2SO_4**	**186**	**27 h at 10 mA/cm^2**	**This work**
RuCo@NG/N-GNs	0.5 M H_2SO_4	209	10 h at 10 mA/cm^2	1
1D-RuO_2-CN_x	0.5 M H_2SO_4	250	lost ~32% current after 55 h of scan	2
IrO_2-BN-rGO	0.5 M H_2SO_4	300	45 h at 10 mA/cm^2 and 5 mA/cm^2	3
$NaRuO_2$ nanosheets	0.1 M $HClO_4$	255	6 h at 1 mA/cm^2	4
Cu-doped RuO_2	0.5 M H_2SO_4	188	8 h at 10 mA/cm^2	5
a/c RuO_2	0.1 M $HClO_4$	205	60 h at 10 mA/cm^2	6
$Cr_{0.6}Ru_{0.4}O_2$	0.5 M H_2SO_4	178	10 h at 10 mA/cm^2	7
RuO_2/$(Co, Mn)_3O_4$	0.5 M H_2SO_4	270	24 h at 10 mA/cm^2	8
Sn-RuO_2@NPC	0.5 M H_2SO_4	178	150 h at 10 mA/cm^2	9
COOH-MWNTs	0.5 M H_2SO_4	265	10 h at 10 mA/cm^2	10
2D D-RuO_2/G	0.5 M H_2SO_4	169	2000 cycles	11
RuB_2	0.5 M H_2SO_4	223	10 h at 10 mA/cm^2	12
Ru@IrO_x	0.05 M H_2SO_4	282	24h at 1.55 V	13
RuMn NSBs	0.5 M H_2SO_4	196	125 h at 10 mA/cm^2 for RuMn NSBs-250||RuMn NSBs-300	14
3D Ru/RuO_2@N-rGO	0.5 M H_2SO_4	234	10 h at10 mA/cm^2 in 1.0 M KOH for Ru/RuO_2@N-rGO||Ru/RuO_2@N-rGO	15
Zn-doped RuO_2	0.5 M H_2SO_4	206	30 h at 10 mA/cm^2	16

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