Highly Stable One-Dimensional Pt Nanowires with Modulated Structural Disorder towards Oxygen Reduction Reaction.

Fanpeng Kong[1, 2], Mohammad Norouzi Banis[2], Lei Du[1], Lijie Zhang[3], Lei Zhang[2], Junjie Li[2], Kieran Doyle-Davis[2], Jianneng Liang[2], Qingsong Liu[1], Xiaofei Yang[2], Ruying Li[2], Chunyu Du[1], Geping Yin[1]*, Xueliang Sun[2]*

[1]MIIT Key Laboratory of Critical Materials Technology for New Energy Conversion and Storage, Harbin Institute of Technology, 150001, China.

[2]Department of Mechanical and Materials Engineering, University of Western Ontario, London, ON N6A 5B9, Canada.

[3]Hunan Provincial Key Laboratory of Low-Dimensional Structural Physics and Devices, School of Physics and Electronics, Hunan University, Changsha 410082, China

Corresponding author: xsun9@uwo.ca, yingphit@hit.edu.cn

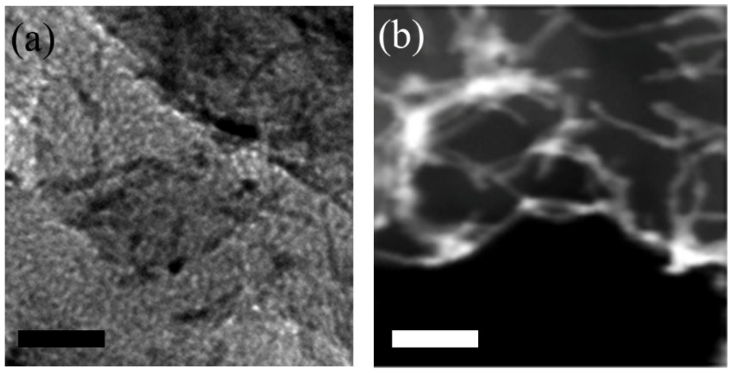

Figure S1. (a)TEM image and (b) HAADF-STEM image of Pt NWs. The scale bar is 20 nm.

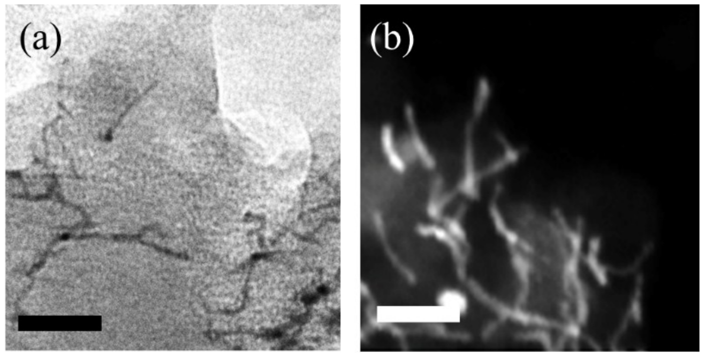

Figure S2. (a)TEM image and (b) HAADF-STEM image of PtNi NWs. The scale bar is 20 nm.

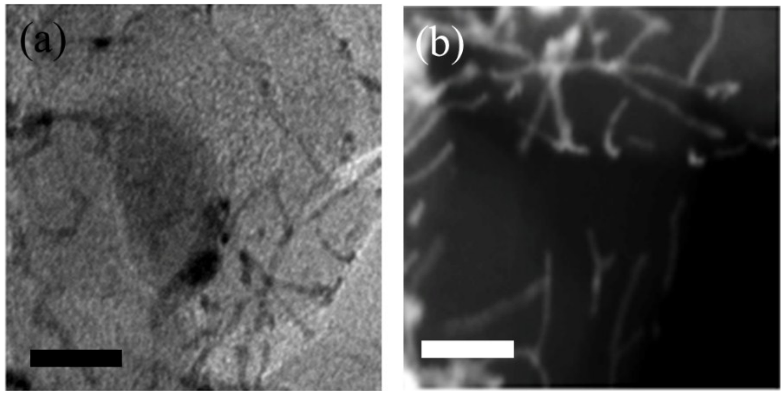

Figure S3. (a)TEM image and (b) HAADF-STEM image of D-O_2-Pt NWs. The scale bar is 20 nm

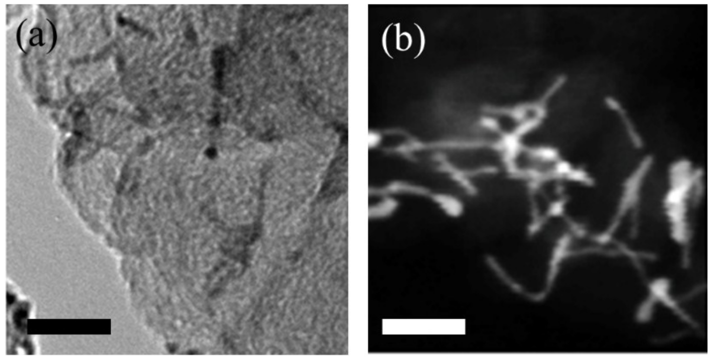

Figure S4. (a)TEM image and (b) HAADF-STEM image of D-Ar-Pt NWs. The scale bar is 20 nm

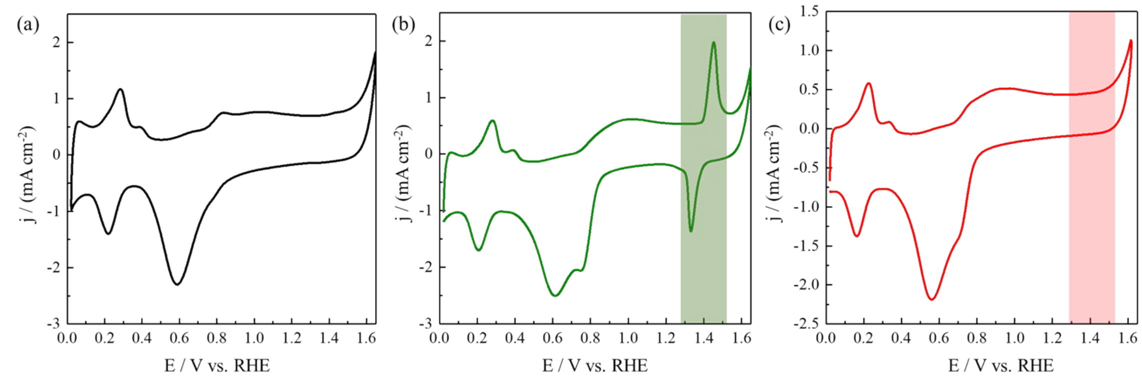

Figure S5. (a) The CV curve of 1st cycle of D-Ar-Pt NWs in oxygen saturated 0.1 M NaOH. (b) The CV curve of 50th cycle of D-Ar-Pt NWs in oxygen saturated 0.1 M NaOH. (c) The CV curve of 50th cycle of D-O_2-Pt NWs in oxygen saturated 0.1 M NaOH.

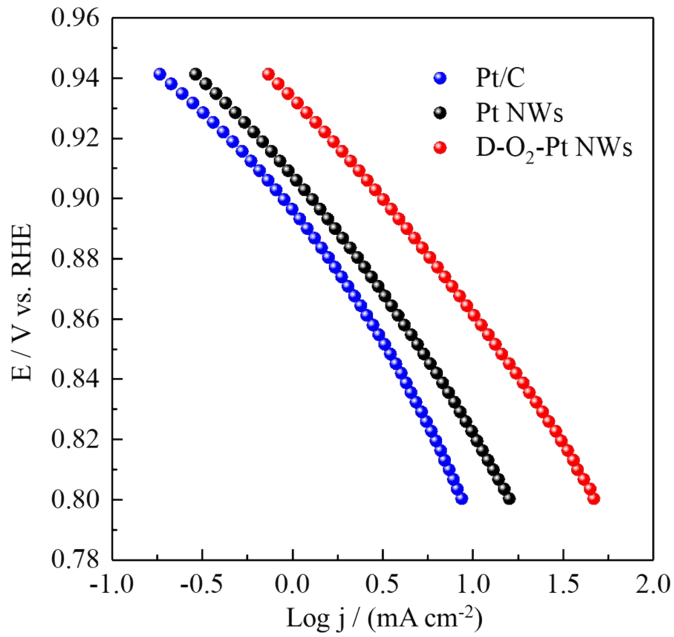

Figure S6. Tafel plots of Pt/C, Pt NWs and D-O_2-Pt NWs for ORR.

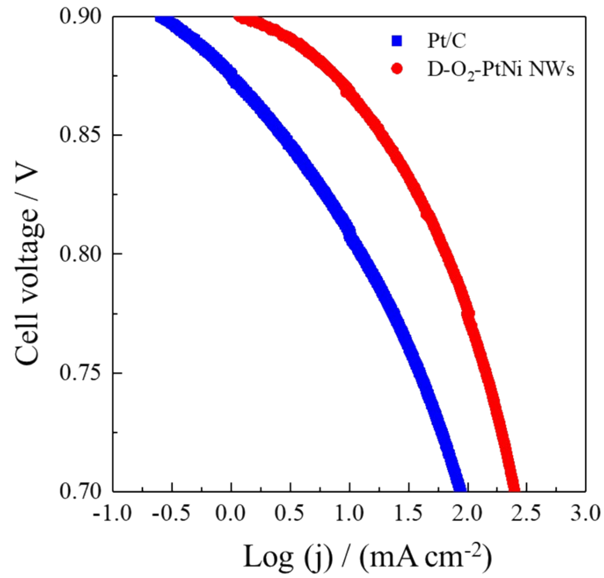

Figure S7. Tafel plots of Pt/C and D-O_2-Pt NWs of MEA for H_2-air fuel cells.

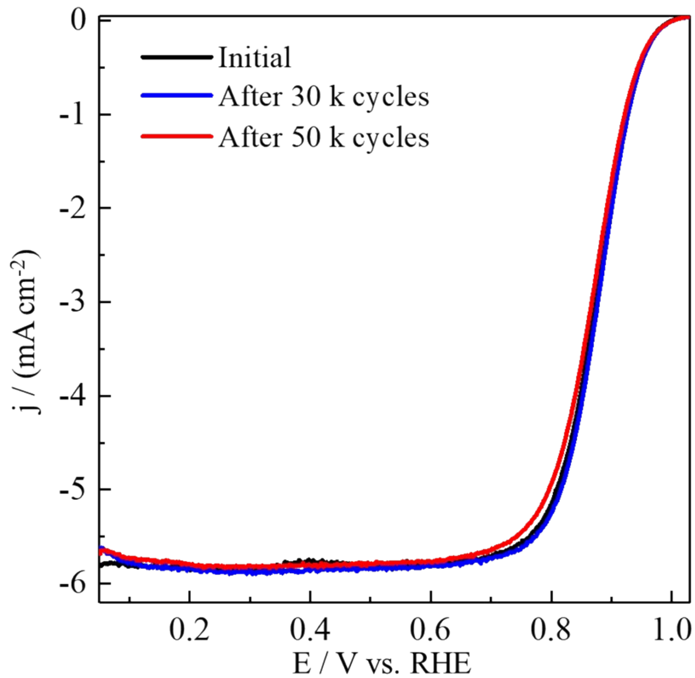

Figure S8. Polarization curves of Pt NWs in oxygen saturated 0.1 $HClO_4$ before and after 30 000 and 50 000 potential cycles between 0.6 and 1.0 V versus RHE.

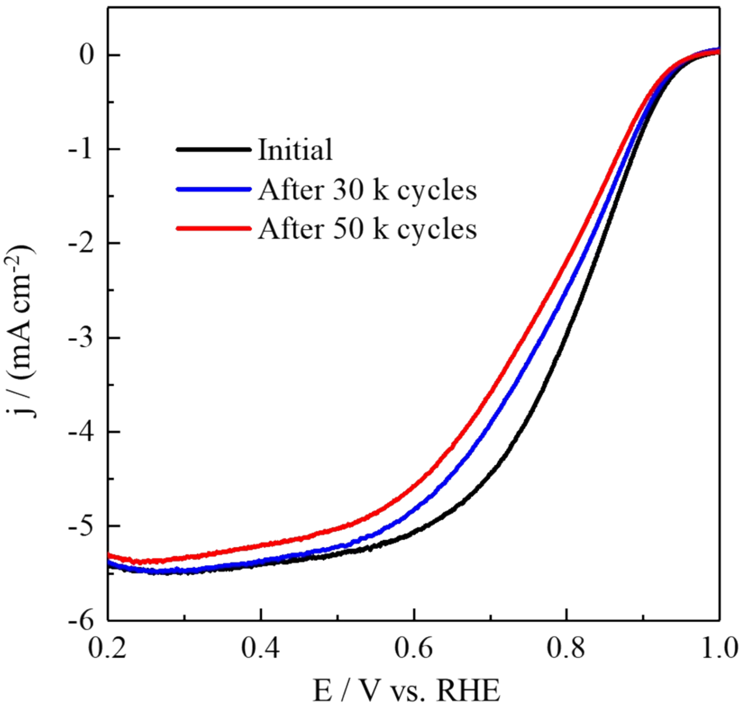

Figure S9. Polarization curves of Pt/C in oxygen saturated 0.1 $HClO_4$ before and after 30 000 and 50 000 potential cycles between 0.6 and 1.0 V versus RHE. The insert image is the HAADF-STEM image of Pt/C after stability test.

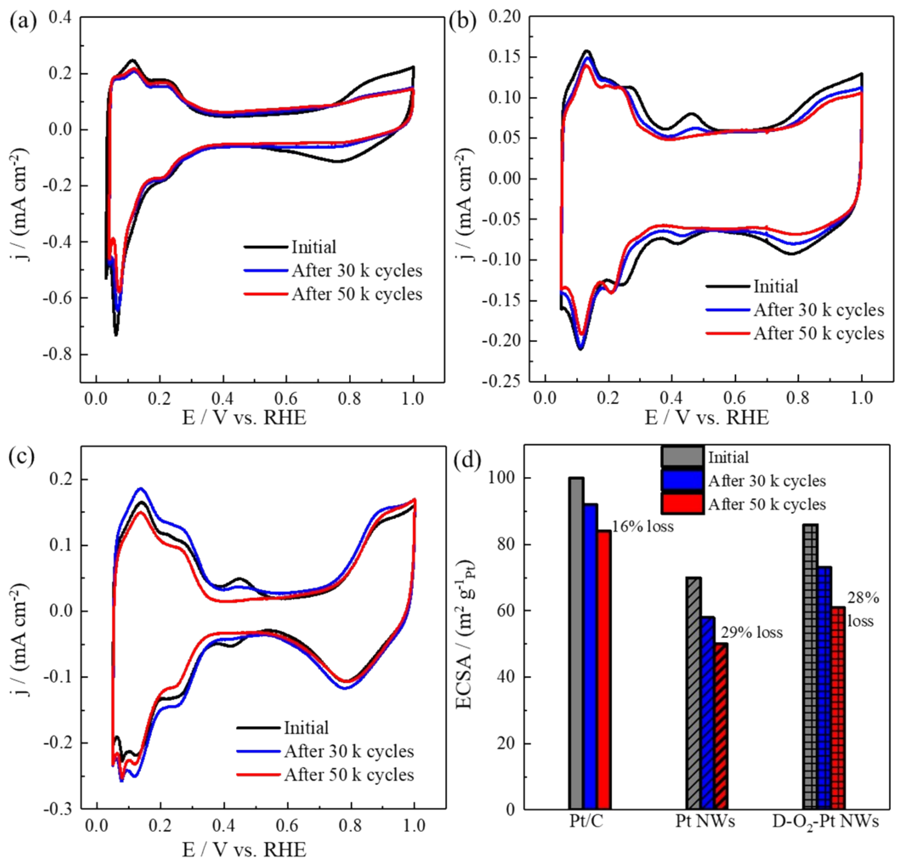

Figure S10. CV of Pt/C (a), Pt NWs (b) and D-O_2-Pt NWs (c) before and after stability test in Ar saturated 0.1 M $HClO_4$. (d) Electrochemical surface area of Pt/C, Pt NWs and D-Pt NWs before and after stability test.

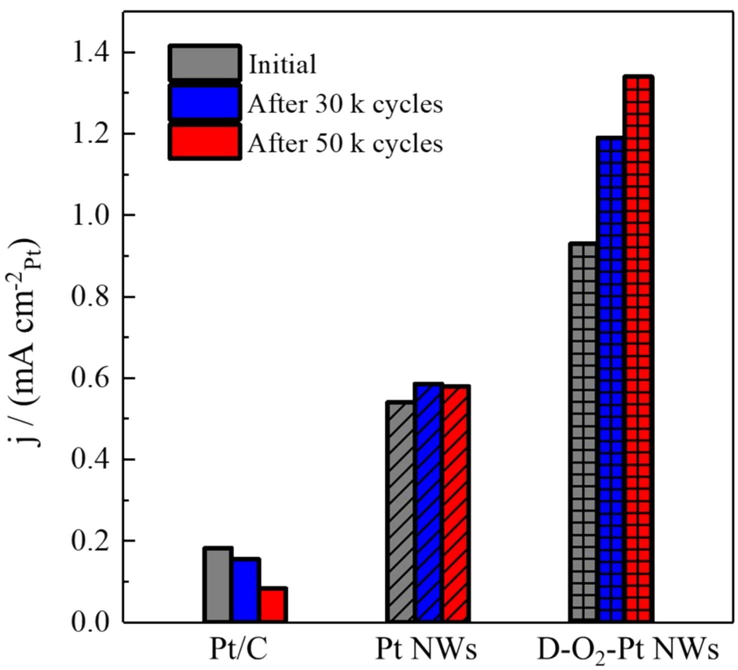

Figure S11. Bar chart of specific activity of Pt/C, Pt NWs and D-O_2-Pt NWs before and after stability test.

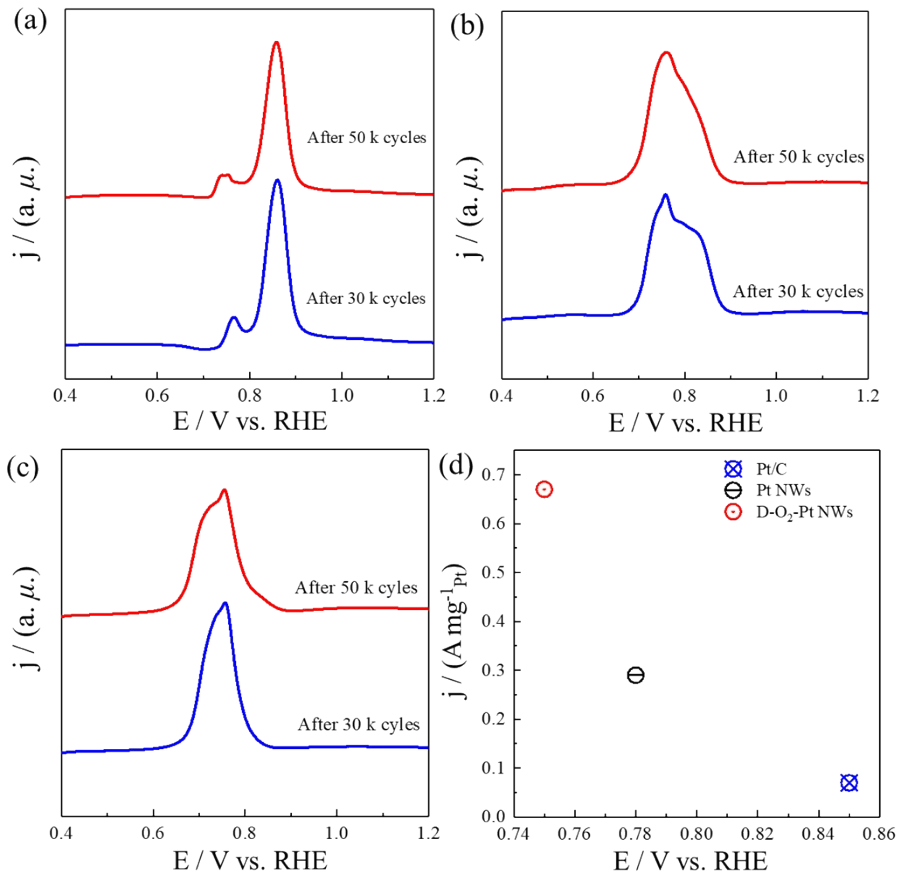

Figure S12. CO stripping curves on Pt/C (a), Pt NWs (b)and D-O_2-Pt NWs (c) after 30 k and 50 k cycles. (d) The relationship between mass activity at 0.9 V and density of defects, estimated by average CO oxidation potential after 50 k cycles.

Table S1. Peak position of Pt 4f and relative content of Pt metallic and oxidized state in Pt NWs, PtNi NWs and D-O_2-Pt NWs.

Samples	Peak position		Relative content	
	Pt $4f_{7/2}$ (eV)	Pt $4f_{5/2}$ (eV)	Pt (0) / %	Pt (II) / %
Pt NWs	71.27	74.62	77	23
PtNi NWs	70.85	74.2	75	25
D-O_2-Pt NWs	71.26	74.6	69	31

Table S2. Activity and stability for ORR of D-O_2-Pt NWs in this work and several results of representative Pt based catalysts from recent published work.

Catalysts	Mass activity (A mg^{-1}_{Pt})	Performance loss	Cycles	Reference
H-PtFe@NC	0.99	27%	20k	Ref 1
Rh doped Pt-Ni octahedra	0.82	12.20%	8k	Ref 2
Pt_1Ni_1 octahedra	1.6	60%	4k	Ref 3
Octahedral Pt nanocages	0.75	36%	10k	Ref 4
$Pd_xNi_{(1-x)}$@Pt_{ML}	1.45	11.50%	12k	Ref 5
$Pt_{2.5}Ni$ octahedra	3.3	40	5k	Ref 6
Pd@Pt nanoparticles	0.78	17.90%	10k	Ref 7
PtNi nanoparticles	0.8	45%	10k	Ref 8
PtNiCo octahedra	0.5	50%	4k	Ref 9
ALD ZrO_2@Pt/NCNT	0.28	8%	4k	Ref 10
Mo-Pt_3Ni octahedra	6.98	5.50%	8k	Ref 11
Rh-Pt nanowires	1.41	9.20%	10k	Ref 12
Pt nanoplate	1.62	28%	10k	Ref 13
$L1_0$FePt/Pt	0.71	3%	10k	Ref 14
Pd@Pt concave decahedra	1.6	55%	10k	Ref 15
Pt icosahedra	1.28	40%	5k	Ref 16
Pd@$Pt_{2.7L}$ icosahedra	0.64	44%	10k	Ref 17
Pt skin@Pt_3Ni	0.68	30%	10k	Ref 18
Pt/N-ALDTa_2O_5/C	0.28	10%	10k	Ref 19
Pd@Pt_{2-3L} octahedra	0.48	28%	10k	Ref 20
D-O_2-Pt NWs	0.86	17%	50k	This work

Reference

1. Wang, Q.; Chen, S.; Shi, F.; Chen, K.; Nie, Y.; Wang, Y.; Wu, R.; Li, J.; Zhang, Y.; Ding, W.; Li, Y.; Li, L.; Wei, Z., Structural Evolution of Solid Pt Nanoparticles to a Hollow PtFe Alloy with a Pt-Skin Surface via Space-Confined Pyrolysis and the Nanoscale Kirkendall Effect. *Advanced materials* **2016,** *28* (48), 10673-10678.

2. Beermann, V.; Gocyla, M.; Willinger, E.; Rudi, S.; Heggen, M.; Dunin-Borkowski, R. E.; Willinger, M. G.; Strasser, P., Rh-Doped Pt-Ni Octahedral Nanoparticles: Understanding the Correlation between Elemental Distribution, Oxygen Reduction Reaction, and Shape Stability. *Nano letters* **2016,** *16* (3), 1719-25.

3. Chunhua Cui, L. G., Marc Heggen, Stefan Rudi and Peter Strasser, Compositional segregation in shaped Pt alloy nanoparticles and their structural behaviour during electrocatalysis. *Nature materials* **2013,** *12*.

4. Zhang, L.; Roling, L. T.; Wang, X.; Vara, M.; Chi, M.; Liu, J.; Choi, S. I.; Park, J.; Herron, J. A.; Xie, Z.; Mavrikakis, M.; Xia, Y., Platinum-based nanocages with subnanometer-thick walls and well-defined, controllable facets. *Science* **2015,** *349* (6246), 412-6.

5. Luo, L.; Zhu, F.; Tian, R.; Li, L.; Shen, S.; Yan, X.; Zhang, J., Composition-Graded PdxNi1–x Nanospheres with Pt Monolayer Shells as High-Performance Electrocatalysts for Oxygen Reduction Reaction. *ACS Catalysis* **2017,** *7* (8), 5420-5430

6. Choi, S. I.; Xie, S.; Shao, M.; Odell, J. H.; Lu, N.; Peng, H. C.; Protsailo, L.; Guerrero, S.; Park, J.; Xia, X.; Wang, J.; Kim, M. J.; Xia, Y., Synthesis and characterization of 9 nm Pt-Ni octahedra with a record high activity of 3.3 A/mg(Pt) for the oxygen reduction reaction. *Nano letters* **2013,** *13* (7), 3420-5.

7. Zhang, L.; Zhu, S.; Chang, Q.; Su, D.; Yue, J.; Du, Z.; Shao, M., Palladium–Platinum Core–Shell Electrocatalysts for Oxygen Reduction Reaction Prepared with the Assistance of Citric Acid. *ACS Catalysis* **2016,** *6* (6), 3428-3432.

8. Gan, L.; Heggen, M.; O'Malley, R.; Theobald, B.; Strasser, P., Understanding and controlling nanoporosity formation for improving the stability of bimetallic fuel cell catalysts. *Nano letters* **2013,** *13* (3), 1131-8.

9. Aran-Ais, R. M.; Dionigi, F.; Merzdorf, T.; Gocyla, M.; Heggen, M.; Dunin-Borkowski, R. E.; Gliech, M.; Solla-Gullon, J.; Herrero, E.; Feliu, J. M.; Strasser, P., Elemental Anisotropic Growth and Atomic-Scale Structure of Shape-Controlled Octahedral Pt-Ni-Co Alloy Nanocatalysts. *Nano letters* **2015,** *15* (11), 7473-80.

10. Cheng, N.; Banis, M. N.; Liu, J.; Riese, A.; Li, X.; Li, R.; Ye, S.; Knights, S.; Sun, X., Extremely Stable Platinum Nanoparticles Encapsulated in a Zirconia Nanocage by Area-Selective Atomic Layer Deposition for the Oxygen Reduction Reaction. *Advanced materials* **2015,** *27* (2), 277-281.

11. Huang, X.; Zhao, Z.; Cao, L.; Chen, Y.; Zhu, E.; Lin, Z.; Li, M.; Yan, A.; Zettl, A.; Wang, Y. M.; Duan, X.; Mueller, T.; Huang, Y., High-performance transition metal-doped Pt3Ni octahedra for oxygen reduction reaction. *Science* **2015,** *348* (6240), 1230-4.

12. Huang, H.; Li, K.; Chen, Z.; Luo, L.; Gu, Y.; Zhang, D.; Ma, C.; Si, R.; Yang, J.; Peng, Z.; Zeng, J., Achieving Remarkable Activity and Durability toward Oxygen Reduction Reaction Based on Ultrathin Rh-Doped Pt Nanowires. *Journal of the American Chemical Society* **2017,** *139* (24), 8152-8159.

13. Liu, H.; Zhong, P.; Liu, K.; Han, L.; Zheng, H.; Yin, Y.; Gao, C., Synthesis of ultrathin platinum nanoplates for enhanced oxygen reduction activity. *Chemical science* **2018,** *9* (2), 398-404.

14. Li, J.; Xi, Z.; Pan, Y. T.; Spendelow, J. S.; Duchesne, P. N.; Su, D.; Li, Q.; Yu, C.; Yin, Z.; Shen, B.; Kim, Y. S.; Zhang, P.; Sun, S., Fe Stabilization by Intermetallic L10-FePt and Pt Catalysis Enhancement in L10-FePt/Pt Nanoparticles for Efficient Oxygen Reduction Reaction in Fuel Cells. *Journal of the American Chemical Society* **2018,** *140* (8), 2926-2932.

15. Wang, X.; Vara, M.; Luo, M.; Huang, H.; Ruditskiy, A.; Park, J.; Bao, S.; Liu, J.; Howe, J.; Chi, M.; Xie, Z.; Xia, Y., Pd@Pt Core-Shell Concave Decahedra: A Class of Catalysts for the Oxygen Reduction Reaction with Enhanced Activity and Durability. *Journal of the American Chemical Society* **2015,** *137* (47), 15036-42.

16. Wang, X.; Figueroa-Cosme, L.; Yang, X.; Luo, M.; Liu, J.; Xie, Z.; Xia, Y., Pt-Based Icosahedral Nanocages: Using a Combination of {111} Facets, Twin Defects, and Ultrathin Walls to Greatly Enhance Their Activity toward Oxygen Reduction. *Nano letters* **2016,** *16* (2), 1467-71.

17. Wang, X.; Choi, S. I.; Roling, L. T.; Luo, M.; Ma, C.; Zhang, L.; Chi, M.; Liu, J.; Xie, Z.; Herron, J. A.; Mavrikakis, M.; Xia, Y., Palladium-platinum core-shell icosahedra with substantially enhanced activity and durability towards oxygen reduction. *Nature communications* **2015,** *6*, 7594.

18. Zhang, B.-W.; Zhang, Z.-C.; Liao, H.-G.; Gong, Y.; Gu, L.; Qu, X.-M.; You, L.-X.; Liu, S.; Huang, L.; Tian, X.-C.; Huang, R.; Zhu, F.-C.; Liu, T.; Jiang, Y.-X.; Zhou, Z.-Y.; Sun, S.-G., Tuning Pt-skin to Ni-rich surface of Pt 3 Ni catalysts supported on porous carbon for enhanced oxygen reduction reaction and formic electro-oxidation. *Nano Energy* **2016,** *19*, 198-209.

19. Song, Z.; Banis, M. N.; Zhang, L.; Wang, B.; Yang, L.; Banham, D.; Zhao, Y.; Liang, J.; Zheng, M.; Li, R.; Ye, S.; Sun, X., Origin of achieving the enhanced activity and stability of Pt electrocatalysts with strong metal-support interactions via atomic layer deposition. *Nano Energy* **2018,** *53*, 716-725.

20. Park, J.; Zhang, L.; Choi, S. I.; Roling, L. T.; Lu, N.; Herron, J. A.; Xie, S. F.; Wang, J. G.; Kim, M. J.; Mavrikakis, M.; Xia, Y. N., Atomic Layer-by-Layer Deposition of Platinum on Palladium Octahedra for Enhanced Catalysts toward the Oxygen Reduction Reaction. *ACS nano* **2015,** *9* (3), 2635-2647