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# Phase Selective Synthesis of Unique Cobalt Telluride Nanofleeces for Highly Efficient Oxygen Evolution Catalyst \*\*

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**Abstract:** Co-based nanomaterials have been intensively explored as promising noble metal free oxygen evolution reaction (OER) electrocatalysts. Herein, we first report phase selective synthesis of novel hierarchical CoTe<sub>2</sub> and CoTe nanofleeces for efficient OER catalyst. The CoTe<sub>2</sub> nanofleeces exhibited excellent electrocatalytic activity and stablity for OER in alkaline media. It has been discovered that the CoTe<sub>2</sub> catalyst exhibited superior OER activity to the CoTe catalyst and comparable to the state-of-the-art RuO<sub>2</sub> catalyst. Density functional theory calculations showed that the binding strength and lateral interaction of the reaction intermediates on CoTe<sub>2</sub> and CoTe are essential for the order of their overpotential and the trend variation at different condition. This study provides value insights for rational design of noble metal free OER catalysts with high performance and low cost by use of Co-based chalcogenides.

Oxygen evolution reaction (OER) plays a significant role in many electrochemical processes such as water splitting and solar fuel synthesis.<sup>[1]</sup> Design and synthesis of active, stable, and low-cost catalytic materials for water splitting is pivotal to the development of sustainable energy sources for powering fuel cells.<sup>[2]</sup> In practice, however, large-scale electrochemical production of hydrogen from water splitting is greatly constrained by two fundamental limitations: the high overpotentials of the OER, and the lack of stability of electrode materials.<sup>[3]</sup> Currently, the most widely used catalysts for OER in electrolysis cells are ruthenium (Ru) and iridium (Ir) oxides, although these elements are among the rarest elements on earth.<sup>[4]</sup> Therefore, there is an urgent demand of alternative catalysts which are not only suitable for large-scale adoption but also remain high efficiency.

In the last few decades, cobalt (Co)-based OER catalysts have been developed for potential applications of water oxidation in alkaline environments, including nanostructured  $Co_3O_4^{[5]}$  and related hybrids,<sup>[6]</sup>  $Co_2O_3$  nanoparticles,<sup>[7]</sup>

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amorphous cobalt-phosphate-based material (Co-Pi),<sup>[8]</sup> Co-Pi/ $\alpha$ -Fe<sub>2</sub>O<sub>3</sub> composites,<sup>[9]</sup> Co-OEC (oxygen evolving complex),<sup>[10]</sup> and so on. Besides advantages such as earth-abundant, low cost and high yield, these Co-based materials can generate O<sub>2</sub> under mild conditions and modest overpotentials. Previous efforts have demonstrated that CoSe<sub>2</sub> nanobelts and CoSe<sub>2</sub>/Mn<sub>3</sub>O<sub>4</sub> composites are promising OER catalysts in alkaline media.<sup>[111]</sup> Here, we show overwhelming interests in Te, as an element among the transition metal-based chalcogenides, because compared to O, S and Se atoms, Te atom exhibits more metallic character, which is a favourable property for electrocatalysts due to better electron conductivity.<sup>[12]</sup>

Although many metal tellurides have been synthesized, researches into cobalt telluride hierarchical structures and their applications are still rare.<sup>[13]</sup> Among various fabricating methods, Te nanowire directed synthesis is emerging as one of the most popular strategies for the fabrication of 1D telluride nanostructures,<sup>[14]</sup> because ultrathin nanowires are desirable templates for the fabrication of 1D nanostructures.[15] Herein, we report a facile chemical transformation process for phase selective synthesis of uniform hierarchical CoTe<sub>2</sub> and CoTe nanofleeces using ultrathin Te nanowires as templates, which shows highly efficient OER performances. The CoTe<sub>2</sub> catalyst exhibited superior OER activity to the CoTe catalyst and comparable to the state-of-the-art RuO<sub>2</sub> catalyst in basic media. Furthermore, such hierarchical CoTe<sub>2</sub> nanofleeces also perform very stable in 0.1 M KOH electrolyte. Density functional theory (DFT) calculations showed that the distinct binding strength and lateral interaction of the reaction intermediates on CoTe<sub>2</sub> and CoTe is essential for the relative order of their overpotential and trend variation at different conditions.

Firstly, ultrathin Te nanowires (Figure S1) were systhesized by the modified method described previously.<sup>[16]</sup> The hierarchical CoTe<sub>2</sub> nanofleeces were typically synthesized through an polyol reduction approach using the ultrathin Te nanowires as templates. The X-ray diffraction (XRD) patterns (Figure S2) of the samples obtained at 200 °C and 220 °C can be indexed to orthorhombic  $CoTe_2$  (JCPDS 11-0553) and hexagonal CoTe (JCPDS 34-0420), respectively. The Co:Te atomic ratio determined by Energy-dispersive X-ray spectroscopy (EDS) analysis (Figure S3) agrees well with the XRD result. The X-ray photoelectron spectroscopy (XPS) data in Figure S4a reveal the electron-binding energies of Co in CoTe<sub>2</sub> and CoTe both correspond to Co2+ cations.<sup>[17]</sup> Furthermore, synchrotron X-ray absorption spectroscopy analysis was also performed to further determine the oxidation states of the cobalt (Figure S4b), which was demonstrated to be +2 for both  $CoTe_2$  and CoTe as well.

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Figure 1. SEM images of hierarchical  $CoTe_2$  (a) and CoTe (d) nanostructures. HRTEM image of one single  $CoTe_2$  (b) and CoTe (e) nanofleece. (c, f) HAADF-STEM characterization of one single nanofleece and the corresponding elemental mappings of Te (red) and Co (green).

The morphologies and sizes of the products were studied by field-emission scanning electron microscopy (FESEM) and transmission scanning electron microscopy. Figure 1a shows a typical SEM image of the hierarchical CoTe<sub>2</sub> structures with mean diameter of about 200 nm and length up to several micrometers. The SEM image indicates that a large amount of small nanofleeces align perpendicularly to the growth axis, forming remarkable 1D hierarchical nanostructures. The representative SEM image of as-prepared products clearly reveals that the small nanofleeces have diameters of mere ~10 nm and lengths of tens to hundreds nanometers. Figure 1b shows a typical HRTEM image of a single CoTe<sub>2</sub> nanofleece, revealing that the CoTe<sub>2</sub> nanofleeces are structurally uniform with interlayer spacing about 2.71 Å, which corresponds to (120) lattice plane of the orthorhombic CoTe2. The elemental mappings (Figure 1c) indicate that Co and Te elements are uniformly distributed in the product. Figure 1d shows a typical SEM image of CoTe nanofleeces, which have the similar hierarchical structure with the CoTe<sub>2</sub> nanofleeces. A typical HRTEM image (Figure 1e) of a single CoTe nanofleece reveals that the CoTe hierarchical structures are structurally uniform with interlayer spacing about 2.86 Å, which corresponds to (101) lattice plane of the hexagonal CoTe. Moreover, the N2 adsorption-desorption isotherms of the product (Figure S5) reveal that the hierarchical CoTe<sub>2</sub> and CoTe nanofleeces have BET surface areas of 97 and 75 m<sup>2</sup> g<sup>-1</sup>, respectively, which are fairly high for transition metal chalcogenide materials. Such a high surface area should be attributed to the tiny branched nanofleeces with an average diameter of about 10 nm.

To understand the formation mechanism of hierarchical CoTe<sub>2</sub> nanofleeces, the growth process was carefully tracked by time dependent experiments. We used XRD to analyze the phase

evolution of this reaction (Figure S6). After keeping the solution at 110 °C for 1 h, all of the peaks could be indexed to the hexagonal phase of Te. When the reaction temperature was increased to 200 °C for 15 min, trace peaks of  $CoTe_2$  appeared in the XRD pattern, which indicated that  $CoTe_2$  began to form. Upon prolonging reaction time to 30 min, the product consisted predominantly of  $CoTe_2$ , although the hexagonal phase of Te was also present. No hexagonal Te diffraction peaks were observed when the reaction time was up to 1 h, which indicated that the Te was completely transformed into  $CoTe_2$ .



**Figure 2.** (a) Schematic illustration of the proposed growth mechanism for hierarchical CoTe<sub>2</sub> nanostructures. (b) SEM image of the product obtained at 110 °C for 60 min; SEM images of the products obtained at 200 °C for (c) 0 min; (d) 5 min; (e) 10 min; (f) 15 min; (g) 20 min; (h) 30 min; (i) 60 min; (j) 120 min.

The samples taken from the synthesis mixtures at different time intervals were then observed by SEM to capture the morphology evolution process (Figure 2). Figure 2a shows the schematic illustration of the proposed growth mechanism for hierarchical CoTe<sub>2</sub> nanostructures. In order to boil off the trace amount of water, we first heated the solution at 110 °C for 1 h. During this process, the diameter of the nanowires grew from 7 nm to ~30 nm, and the surface of the nanowire turned much rougher (Figure S7). When the temperature rose to 200 °C, plenty of bumps appeared on the surface of nanowires. With the extension of time, more and more bumps came out and gradually grew into long nanofleeces, which eventually covered the whole surface of nanowires when the reaction lasted for 1 h. As the reaction proceeded to 2 h, all the nanofleeces continued to grow, and the average diameter reached to about 20 nm. Note that we have conducted a series of experiments to optimize the conditions for synthesis of high-quality hierarchical  $\mathsf{CoTe}_2$  nanostructures. In our experiments, we found that the composition of surfactants (ratio of OAm/OA), the amount of Co(acac)<sub>2</sub>, the reaction temperature and time play important roles in the formation of uniform hierarchical CoTe22 nanostructures (Figure S8-S11).

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Figure 3. (a) Polarization curves for OER of several catalysts as indicated. (b) Tafel plot (overpotential versus log current) derived from (a). (c, d) OER polarization curves of hierarchical CoTe<sub>2</sub> and CoTe nanofleeces before and after different cycles of accelerated stability test.

To appraise the catalytic properties of the new hierarchical CoTe<sub>2</sub> nanostructures for electrochemical oxidation of water to oxygen, film of hierarchical CoTe2 nanostructures was prepared onto glassy carbon electrodes for cyclic voltammetry (CV) in O2saturated 0.1 M KOH. Similar measurements for hierarchical CoTe nanostructures, Pt/C (20-wt.%) and commercial RuO<sub>2</sub> reference were also performed for comparison. Figure 3a shows their linear sweeps in an anodic direction, from which we can see that the hierarchical CoTe<sub>2</sub> nanostructures exhibit greater current as compared to hierarchical CoTe nanostructures, RuO<sub>2</sub> and Pt/C references. The current density of 10 mA cm<sup>-2</sup> can be achieved at a small overpotential of ~0.357 V for our catalyst, which is better than the best reported Co<sub>3</sub>O<sub>4</sub>/graphene catalyst with the similar loading (0.25 mg  $\mbox{cm}^{-2}).^{[6]}$  Note here that the overpotential of current density at 10 mA cm<sup>-2</sup> of the CoTe<sub>2</sub> catalyst is comparable to or smaller than those of the wellstudied Co-based OER catalysts in the literature (Table S1). Figure 3b shows that the Tafel slope of the hierarchical CoTe<sub>2</sub> nanostructures is ~32 mV/decade, which is smaller than that of RuO<sub>2</sub>, hierarchical CoTe nanostructures, and previously reported Co-based OER catalysts such as CoSe<sub>2</sub>/Mn<sub>3</sub>O<sub>4</sub> composites,<sup>[11a]</sup> Co<sub>3</sub>O<sub>4</sub><sup>[5]</sup> and Co<sub>3</sub>O<sub>4</sub>/graphene hybrids<sup>[6]</sup> at similar loading, and comparable to the best known OER catalysts in basic media.<sup>[18]</sup> We calculated a high TOF of 0.20 s<sup>-1</sup> associated with CoTe<sub>2</sub> nanostructures at overpotential of 350 mV in 0.1 M KOH, which was higher than 0.12 s<sup>-1</sup> of CoTe nanostructures and comparable to 0.22 s<sup>-1</sup> of RuO<sub>2</sub>.

In addition, the hierarchical CoTe<sub>2</sub> nanostructures catalyst also exhibited high stability for OER. Figure 3c shows that after 2,000 potential cycles, the CoTe<sub>2</sub> nanostructures almost afforded the same j-V curves as initial catalyst, only with negligible drops of the anodic current, while the anodic current showed a loss of about 80% and 70% for the hierarchical CoTe nanostructures (Figure 3d) and the state-of-the-art RuO<sub>2</sub> (Figure S12) at 1.60 V versus RHE, respectively. We performed XRD and XPS measurements after 2,000 potential cycles (Figure S13, S14), which showed that no obvious phase and valence changes were observed after long-term electrolysis. As shown in Figure S13c, d, the original hierarchical nanostructure of  $CoTe_2$  was still kept after 2,000 potential cycles electrolysis, while the morphology of CoTe was destroyed, which should be responsible to the different stabilities of  $CoTe_2$  and CoTe catalysts. The excellent stability of the  $CoTe_2$  can be evidenced further from the chronoamperometric measurements. As shown in Figure S15, at the current density of 10 mA cm<sup>-2</sup>, the overpotential produced in the  $CoTe_2$  catalyst exhibited no measurable increase over 24 h of continuous operation. This extraordinary durability shows promise for practical applications of the catalysts over the long term.

We then studied the OER activities of the products obtained at different time intervals (Figure S16a). The low OER activities of the products obtained at 15 min and 30 min should be attributed to poor crystallinity and impurity of remnant Te nanowires, while the low OER activities of the products obtained at 2 h could be the result of low surface area. We also studied the OER activities of the products obtained at different temperatures (Figure S16b). The low OER activities of the products obtained at 180 °C should also be attributed to poor crystallinity and impurity of remnant Te nanowires, while the low OER activities of the products obtained at 250 °C should be due to the phase of CoTe and the even lower surface area.



Figure 4. Standard free energy diagram for OER at zero potential, equilibrium potential and theoretical onset external potential. (a) and (b) for CoTe(101) and CoTe<sub>2</sub>(120) without pre-adsorbed O<sup>\*</sup>, (c) and (d) for CoTe(101) and CoTe<sub>2</sub>(120) with pre-adsorbed O<sup>\*</sup> (0.5 ML).

To rationalize the superior electrochemical performance of cobalt telluride and dependence on the phase, we propose that high surface area, electrical conductivity and activity of CoTe<sub>2</sub> and CoTe towards the reaction intermediates are essential. First the hierarchical structure of CoTe<sub>2</sub> nanofleeces offers large surface areas, which increases contact between the electrolytes and electrode materials, thus enhancing the electrocatalytic activities of the electrodes. This can be justified by the larger BET area of 97 and 75 m<sup>2</sup> g<sup>-1</sup> for CoTe<sub>2</sub> and CoTe, respectively (Figure S5). To be more relevant with electrochemical active surface area of materials, the capacitance of the corresponding double layer of CoTe<sub>2</sub> and CoTe nanostructures were measured. As shown in Figure S17, the capacitance of CoTe<sub>2</sub> electrode is 0.357 mF cm<sup>-2</sup>, while the capacitance of CoTe electrode is 0.266 mF cm<sup>-2</sup>. Therefore, the CoTe<sub>2</sub> catalysts have a higher electrochemical active surface area than that of CoTe, which is

in favor of enhancing the electrochemical activity. Second, the kinetics of electrode reactions for CoTe<sub>2</sub> and CoTe nanostructures were probed by electrochemical impedance spectroscopy (EIS) technique (Figure S18). The smaller R<sub>ct</sub> value of CoTe<sub>2</sub> electrode than that of CoTe suggests its higher electrical conductivity.

DFT investigation (see Supporting Information for details) of the two dominated facets CoTe(101) and CoTe<sub>2</sub>(120) (Figure S19 and S20) showed that CoTe<sub>2</sub> and CoTe bind differently with the reaction intermediates involved in OER.[19] The standard reaction free energy profile  $\Delta G$  (Figure 4), taking into account of the electrochemical condition,<sup>[19b, 20]</sup> shows that the third step is the potential limiting step (see Table S3 for details), which is consistent with previous calculations on metal or metal oxides in acidic conditions.<sup>[19c, 20-21]</sup> At a lower coverage of 0.5 ML (with respect to surface five-fold Co atoms), the corresponding overpotential n derived is 1.01 and 0.92 V for CoTe<sub>2</sub>(120) and CoTe(101), respectively. The larger  $\eta$  of CoTe<sub>2</sub>(120) than that of CoTe(101) from the present calculation rationalizes well the observed larger  $\eta$  of CoTe<sub>2</sub> than that of CoTe at low current. With increase of the applied external potential (and the current), the anionic ion OH<sup>-</sup> tends to accumulate at anode forming OH<sup>\*</sup>, O\* and OOH\*, and the surface coverage would increase. By calculating the  $\Delta G$  profile in the presence of 0.5 ML preadsorbed OH\*/O\*/OOH\* (see Figure S21, S22 and Table S2, S3), it is not surprising that the differential binding energies for all intermediates involved are destabilized on both surfaces because of increased lateral repulsion. Interestingly, the extent of destabilization for the intermediates considered on two surfaces are different, especially for O\* and OOH\*. Accordingly, the order of the overpotential  $\eta$  between CoTe<sub>2</sub>(120) and CoTe(101) is reversed with the pre-adsorbed species. This can be seen in free energy profile with pre-adsorbed 0.5 ML O\* plotted in Figure 4C and D. This shows clearly that the different lateral interaction between the reaction intermediates at higher coverage have a great impact on the overpotential. The computational result rationalizes well the trend variation of the electrocatalytic activity of CoTe<sub>2</sub>(120) and CoTe(101) at different condition.

In summary, we have demonstrated a facile chemical transformation process for phase selective synthesis of novel hierarchical CoTe<sub>2</sub> and CoTe nanofleeces using ultrathin Te nanowires as templates. This earth-abundant CoTe<sub>2</sub> catalyst exhibited excellent OER activity and stability in alkaline medium. The high surface area and electrical conductivity of CoTe<sub>2</sub> and CoTe nanostructures played an essential role on their superior electrocatalytic performance. DFT calculations showed that the different binding strength and lateral interaction of the reaction intermediates involved on CoTe<sub>2</sub> and CoTe in OER are essential for the order of the overpotential and the trend variation at different conditions. This study describes the significant potential of designing high performance and low cost OER catalysts from metal tellurides, which is highly demanded for energy conversion technologies.

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**Keywords:** electrocatalyst • cobalt telluride • hierarchical structure • oxygen evolution reaction

- a) Q. Yin, J. M. Tan, C. Besson, Y. V. Geletii, D. G. Musaev, A. E. Kuznetsov, Z. Luo, K. I. Hardcastle, C. L. Hill, Science 2010, 328, 342; b)
   M. W. Kanan, D. G. Nocera, Science 2008, 321, 1072.
- [2] M.-R. Gao, J.-X. Liang, Y.-R. Zheng, Y.-F. Xu, J. Jiang, Q. Gao, J. Li, S.-H. Yu, Nat Commun 2015, 6.
- [3] R. Subbaraman, D. Tripkovic, K. C. Chang, D. Strmcnik, A. P. Paulikas, P. Hirunsit, M. Chan, J. Greeley, V. Stamenkovic, N. M. Markovic, Nat. Mater 2012, 11, 550.
- [4] a) F. A. Frame, T. K. Townsend, R. L. Chamousis, E. M. Sabio, T. Dittrich, N. D. Browning, F. E. Osterloh, J. Am. Chem. Soc. 2011, 133, 7264; b) V. Petrykin, K. Macounova, O. A. Shlyakhtin, P. Krtil, Angew. Chem., Int. Ed. 2010, 49, 4813.
- [5] A. J. Esswein, M. J. McMurdo, P. N. Ross, A. T. Bell, T. D. Tilley, J. Phys. Chem. C 2009, 113, 15068.
- [6] Y. Liang, Y. Li, H. Wang, J. Zhou, J. Wang, T. Regier, H. Dai, Nat. Mater. 2011, 10, 780.
- [7] T.-L. Wee, B. D. Sherman, D. Gust, A. L. Moore, T. A. Moore, Y. Liu, J. C. Scaiano, J. Am. Chem. Soc. 2011, 133, 16742.
- [8] a) Y. Surendranath, M. Dinca, D. G. Nocera, J. Am. Chem. Soc. 2009, 131, 2615; b) D. A. Lutterman, Y. Surendranath, D. G. Nocera, J. Am. Chem. Soc. 2009, 131, 3838.
- [9] a) D. K. Zhong, D. R. Gamelin, J. Am. Chem. Soc. 2010, 132, 4202; b) D.
   K. Zhong, J. Sun, H. Inumaru, D. R. Gamelin, J. Am. Chem. Soc. 2009, 131, 6086.
- [10] S. Y. Reece, J. A. Hamel, K. Sung, T. D. Jarvi, A. J. Esswein, J. J. H. Pijpers, D. G. Nocera, Science 2011, 334, 645.
- [11]a) M. R. Gao, Y. F. Xu, J. Jiang, Y. R. Zheng, S. H. Yu, J. Am. Chem. Soc. 2012, 134, 2930; b) M. R. Gao, W. T. Yao, H. B. Yao, S. H. Yu, J. Am. Chem. Soc. 2009, 131, 7486.
- [12] G. Wu, G. F. Cui, D. Y. Li, P. K. Shen, N. Li, J. Mater. Chem. 2009, 19, 6581.
- [13] a) I. G. McKendry, A. C. Thenuwara, J. Sun, H. Peng, J. P. Perdew, D. R. Strongin, M. J. Zdilla, ACS Catalysis 2016, 6, 7393; b) S. A. Patil, E.-K. Kim, N. K. Shrestha, J. Chang, J. K. Lee, S.-H. Han, ACS applied materials & interfaces 2015, 7, 25914; c) R. Shi, X. Liu, Y. Shi, R. Ma, B. Jia, H. Zhang, G. Qiu, J. Mater. Chem. 2010, 20, 7634; d) H. Fan, Y. Zhang, M. Zhang, X. Wang, Y. Qian, Cryst. Growth Des. 2008, 8, 2838; e) Q. Peng, Y. Dong, Y. Li, Inorg. Chem. 2003, 42, 2174; f) Y. Xie, B. Li, H. Su, X. Liu, Y. Qian, Nanostruct. Mater. 1999, 11, 539.
- [14] a) H. W. Liang, S. Liu, Q. S. Wu, S. H. Yu, Inorg Chem 2009, 48, 4927; b)
  J. Li, X. Tang, L. Song, Y. Zhu, Y. Qian, J. Cryst. Growth 2009, 311, 4467;
  c) P. Zuo, S. Zhang, B. Jin, Y. Tian, J. Yang, J. Phys. Chem. C 2008, 112, 14825.
- [15] a) H. W. Liang, J. W. Liu, H. S. Qian, S. H. Yu, Acc Chem Res 2013, 46, 1450; b) R. L. S. Tan, W. H. Chong, Y. Feng, X. Song, C. L. Tham, J. Wei, M. Lin, H. Chen, J. Am. Chem. Soc. 2016, 138, 10770; c) J. He, Y. Wang, Y. Feng, X. Qi, Z. Zeng, Q. Liu, W. S. Teo, C. L. Gan, H. Zhang, H. Chen, ACS Nano 2013, 7, 2733.
- [16] H. S. Qian, S. H. Yu, J. Y. Gong, L. B. Luo, L. F. Fei, Langmuir 2006, 22, 3830.
- [17] NIST X-ray Photoelectron Spectroscopy Database. http://srdata.nist.gov/xps/Default.aspx.

- [18] a) L. Trotochaud, J. K. Ranney, K. N. Williams, S. W. Boettcher, J. Am. Chem. Soc. 2012, 134, 17253; b) J. Suntivich, K. J. May, H. A. Gasteiger, J. B. Goodenough, Y. Shao-Horn, Science 2011, 334, 1383.
- [19] a) A. Vojvodic, J. K. Norskov, Science 2011, 334, 1355; b) H. Y. Su, Y. Gorlin, I. C. Man, F. Calle-Vallejo, J. K. Norskov, T. F. Jaramillo, J. Rossmeisl, Phys. Chem. Chem. Phys. 2012, 14, 14010; c) M. Bajdich, M. Garcia-Mota, A. Vojvodic, J. K. Norskov, A. T. Bell, J. Am. Chem. Soc. 2013, 135, 13521.
- [20] J. Rossmeisl, A. Logadottir, J. K. Nørskov, Chemical Physics 2005, 319, 178.
- [21] A. Valdes, J. Brillet, M. Gratzel, H. Gudmundsdottir, H. A. Hansen, H. Jonsson, P. Klupfel, G. J. Kroes, F. Le Formal, I. C. Man, R. S. Martins, J. K. Norskov, J. Rossmeisl, K. Sivula, A. Vojvodic, M. Zach, Phys. Chem. Chem. Phys. 2012, 14, 49.

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# COMMUNICATION



Qiang Gao, Chuan-Qi Huang, Yi-Ming Ju, Min-Rui Gao, Jian-Wei Liu, Duo An, Chun-Hua Cui, Ya-Rong Zheng, Wei-Xue Li\*, and Shu-Hong Yu\*



Phase Selective Synthesis of Unique Cobalt Telluride Nanofleeces for Highly Efficient Oxygen Evolution Catalyst

*Hierarchical nanofleees of noble metal free electrocatalyst:* Hierarchical  $CoTe_2$  nanofleeces were successfully synthesized by using ultrathin Te nanowires as templates, which exhibited excellent electrocatalytic activity and stablity for oxygen evolution reaction (OER) in alkaline media. The  $CoTe_2$  catalyst exhibited superior OER activity to the CoTe catalyst and comparable to the state-of-the-art RuO<sub>2</sub> catalyst, which was supported by DFT calculations.