Manipulating dehydrogenation kinetics through dual-doping Co₃N electrode enables highly efficient hydrazine oxidation assisting self-powered H₂ production

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Replacing sluggish oxygen evolution reaction (OER) with hydrazine oxidation reaction (HzOR) to produce hydrogen has been considered as a more energy-efficient strategy than water splitting. However, the relatively high cell voltage in two-electrode system and the required external electric power hinder its scalable applications, especially in mobile devices. Herein, we report a bifunctional P, W co-doped Co₃N nanowire array electrode with remarkable catalytic activity towards both HzOR (−55 mV at 10 mA cm⁻²) and hydrogen evolution reaction (HER, −41 mV at 10 mA cm⁻²). Inspiringly, a record low cell voltage of 28 mV is required to achieve 10 mA cm⁻² in two-electrode system. DFT calculations decipher that the doping optimized H⁺ adsorption/desorption and dehydrogenation kinetics could be the underlying mechanism. Importantly, a self-powered H₂ production system by integrating a direct hydrazine fuel cell with a hydrazine splitting electrolyzer can achieve a decent rate of 1.25 mmol h⁻¹ at room temperature.
The rapidly increasing energy consumption and the deteriorating global environmental concerns have compelled the stringent demand on clean and sustainable energy sources. Hydrogen (H₂), as the energy carrier with the highest energy density and zero carbon emission, has been placed much expectation as one of the most fascinating candidates to change the current fossil fuel dominated energy structure. However, the key challenge originates from the intrinsically sluggish kinetics of anodic oxygen evolution reaction (OER, \(4\text{OH}^– \rightarrow \text{O}_2 + 2\text{H}_2\text{O} + 4e^–\)) involving four-electron-transfer process, which not only lead to the energy wastage, but also further increase the cost due to the utilization of noble metal based electrocatalysts, thus highly limited the large-scale application. Hence, it is highly desired to develop alternative strategy different from fabricating high performance OER electrocatalysts in order to avoid the high energy consumption at the anode.

Recently, it has been demonstrated to possibly overcome this obstacle by replacing anodic OER with thermodynamically more favorable electrocatalytic oxidation of small molecules, including tetrahydroisoquinoline, benzyl alcohol, urea, and hydrazine, which can hugely decrease the cell voltage for H₂ production. Among these, hydrazine reaction (H₂OR, \(\text{N}_2\text{H}_4 + 4\text{OH}^– \rightarrow \text{N}_2 + 2\text{H}_2\text{O} + 4e^–\)) possesses unique feature of tremendously lower theoretical potential of \(-0.33\) V (vs. RHE) compared to that of OER (1.23 V vs. RHE). More importantly, the H₂OR coupled H₂ production (i.e., overall hydrazine splitting, denoted as OHzS) generates N₂ as the only byproduct, which is much safer compared to water splitting producing the mixture of H₂ and O₂, as well as enabling the utilization of separator-free electrolyzer. Some pioneering works have achieved inspiring progress regarding the H₂OR assisted H₂ production. For example, Sun et al. presented that the Ni₃P nanorods grown on Ni foam exhibited superior catalytic activity towards H₂OR and could output 500 mA cm⁻² at a cell voltage of 1.0 V in the two-electrode system. Xia and co-workers reported that the tubular CoSe₂ nanosheets grown on Ni foam could act as bifunctional HER and H₂OR electrocatalysts, which required a cell voltage of 0.164 V to achieve a current density of 10 mA cm⁻² in the two-electrode system. Non-precious Co₁₀Ta intermetallic nanoparticles prepared by Xia’s group shows an onset potential of \(-86\) mV and two times higher specific activity than commercial Pt/C. Despite these progress, there are still several remained challenges in this area. Firstly, it is still unsatisfactory on the relatively high cell voltage in two-electrode system, especially for high current densities, which makes it desired to develop new materials with excellent catalytic activity for both HER and H₂OR. Secondly, at the current infant stage on H₂OR electrocatalysis, the theoretical understanding on the underlying mechanism for new materials is undoubtedly necessary for the development of materials chemistry. More importantly, external electric power is required in current OHzS based H₂ production, which could be a critical hindrance for practical applications in mobile devices and vehicles. Therefore, the proof-of-concept demonstration of integrated system that can use hydrazine as the sole fuel to produce H₂ without external power supply is highly meaningful.

Herein, we present an integrated electrode composed of P, W co-doped Co₃N nanowire arrays in situ grown on nickel foam (denoted as PW-Co₃N NWA/NF) as highly efficient bifunctional electrocatalysts for both H₂OR and HER. Remarkably, it can achieve current density of 10, 200, and 600 mA cm⁻² with required working potential of \(-55, 27,\) and \(127\) mV (vs. RHE) for H₂OR in 1.0 M KOH/0.1 M NH₃H₂ electrolyte, which is superior compared to state-of-the-art values. Excitingly, the PW-Co₃N NWA/NF also exhibits Pt-like activity for HER with a low overpotential of 41 mV at 10 mA cm⁻² and a small Tafel slope of 40 mV dec⁻¹, as well as excellent durability in 1.0 M KOH electrolyte. The potential of PW-Co₃N NWA/NF for H₂ production is further evaluated as both anode and cathode catalyst for overall hydrazine splitting (OHzS), where an ultrasmall operation voltage of 28 mV is needed to achieve current density of 10 mA cm⁻², and only 277 mV is required to reach 200 mA cm⁻², indicating the remarkable results compared with previous literatures. Density functional theory (DFT) calculations indicate that the P/W doping can not only largely decrease the free-energy changes of the dehydrogenation of adsorbed NH₂NH₂ (denoted as *NH₂NH₂), but also make the free energy of adsorbed H (ΔG_H*) more thermoneutral compared to pristine Co₃N. Furthermore, the proof-of-concept self-powered H₂ production system is demonstrated by integrating a direct hydrazine fuel cell (DHZFC) with an OHzS device using PW-Co₃N NWA/NF as the bifunctional catalyst and hydrazine as the sole liquid fuel, with a decent H₂ evolution rate of 1.25 mmol h⁻¹ at room temperature.

Results

Synthesis and characterization of PW-Co₃N nanowire arrays. The P, W co-doped Co₃N nanowire arrays on Ni foam (PW-Co₃N NWA/NF) are synthesized by a facile two-step process, as indicated in Fig. 1a. Firstly, the precursor nanowire arrays are grown on Ni foam through a low temperature hydrothermal method using phosphotungstic acid (denoted as PW₁₂) as the single doping resource for both P and W. Then, the final products can be obtained after thermal annealing treatment in an NH₃ atmosphere at elevated temperatures (see details in Methods). The morphology and structures are characterized using field-emission scanning electron microscopy (FESEM), transmission electron microscopy (TEM) and X-ray diffraction (XRD). Figure 1b, c present the panoramic view of PW-Co₃N NWA/NF in different magnifications, which show well-aligned nanowires uniformly and densely grown on Ni foam. The cross-sectional view (Fig. 1d) clearly indicates the twisted feature of the nanowires, which is different from the PW-Co₃N precursor nanowire arrays with smooth surfaces (Supplementary Fig. 1). The typical TEM image (Fig. 1e) shows that the PW-Co₃N nanowire is composed of interconnected nanoparticles, which could be formed during phase transformation upon the annealing. The high-resolution TEM (HRTEM) image (Fig. 1f) provides clear lattice fringes with interplanar distances of 2.04 and 2.16 Å, respectively, corresponding to the (101) and (002) planes of hexagonal Co₃N phase, which can be further confirmed by the XRD pattern (Supplementary Fig. 2). The P/W doping can be evidenced by element mapping result (Fig. 1g) that exhibits homogeneous distribution of P and W elements throughout the whole nanowire besides Co and N. Figure 1h, i provide aberration-corrected HAADF-STEM images of PW-Co₃N NWA/NF at atomic resolution, with the enlarged image showing the successful doping of W. The W atoms can be seen as bright dots in Co₃N lattice due to Z-contrast in HAADF-STEM image, since the atomic number of W is significantly larger than that of Co. However, the brightness of W atoms is not so obvious due to the relatively thick Co₃N substrate, especially when viewing along the zone axis. We further tilted the TEM holder to make the specimen off the zone axis, so that the lattice of Co₃N cannot be clearly seen, and then the brightness of W showed up (Fig. 1j). The corresponding fast Fourier transformation (FFT) pattern (Fig. 1k) indicates the crystalline Co₃N along the [111] zone axis. The stoichiometric ratio of P: W: Co in PW-Co₃N NWA/NF is about 1:3.5:36.9 calculated from EDS spectrum and...
ICP-AES measurement (Supplementary Fig. 3). Moreover, the doping level can be easily tuned by changing the dosage of PW_{12} during the growth of PW-Co-precursor nanowire arrays, where similar structures can be observed with different doping levels (Supplementary Fig. 4). Moreover, the influence of thermal annealing temperatures on the morphology and crystal structure is systematically investigated. Compared with the sample annealed at 420 °C, lower temperature (350 °C) makes nanowires less orderly while higher temperature (500 °C) gives the similar well-aligned nanowire arrays (Supplementary Fig. 5). However, higher temperature will generate cubic Co_{4}N phase rather than hexagonal Co_{3}N formed at 350 and 420 °C (Supplementary Fig. 6). In order to get insight on the chemical states and further confirm the P/W doping, the comparing investigation of X-ray photoelectron spectroscopy (XPS) characterization on Co_{3}N NWA/NF and PW-Co_{3}N NWA/NF are performed. Their XPS survey spectra (Supplementary Fig. 7) notably indicate the existence of P and W signals besides Co and N, further confirming the successful doping. The high-resolution spectrum of Co 2p in PW-Co_{3}N NWA/NF (Fig. 2a) possesses two peaks at 780.6 and 796.9 eV, respectively, which can be assigned to Co-N bond in Co_{3}N phase. Importantly, these two peaks are positively shifted to higher binding energies in PW-Co_{3}N NWA/NF. Specifically, the deconvoluted peaks at 778.6 and 793.9 eV can be assigned to metallic Co states in Co_{3}N while the peaks at 786.9 and 803.7 eV can be attributed to satellite peaks. Two more peaks located at 782.4 and 799.2 eV could be originated from the surface oxidation, which has also been broadly observed. The high-resolution N 1s spectrum (Fig. 2b) can be deconvoluted to metal-N (397.1 eV) and N-H (399.1 eV) peaks, respectively, which further confirm the formation of nitride. Interestingly, the binding energy of metal-N displays a negative shift after P/W doping, which is consistent to the positive shift of Co peaks. The W 4f (Fig. 2c) and P 2p (Fig. 2d) spectra can be fitted into W-N (33.3 and 34.8 eV) and P-Co bonds (129.1 eV), respectively, besides the peaks at 35.6, 37.5, and 133.4 eV originated from the surface oxidation. These XPS results suggest that the doping of P and W could induce the charge redistribution, and doping could drive the interfacial charge transfer from doped P/W and Co to N, which leads to the peak shift of Co and N. In order to further confirm this phenomenon, the synchrotron-based X-ray absorption near edge structure (XANES) Co L-edge and N K-edge spectra for PW-Co_{3}N NWA/NF and Co_{3}N NWA/NF are further collected, as shown in Fig. 2e, f, respectively. It can be observed that two typical I_{3} and L_{2} peaks of Co L-edge at about 779.3 and 794.9 eV.
exhibit a positive shift after P/W doping\textsuperscript{40}, while those of N K-edge spectra show negative shift accordingly\textsuperscript{41}, which further reveals the possibly existed interfacial charge transfer effect upon doping observed in XPS results.

To disclose the coordination environment of PW-Co\textsubscript{3}N NWA/NF, we further conducted the extended X-ray absorption fine structure (EXAFS) characterization. Figure 3a shows the Co K-edge XANES spectra of PW-Co\textsubscript{3}N, Co\textsubscript{3}N, Co foil and CoO, where Co foil and CoO are used as the reference. The absorption edge of Co\textsubscript{3}N and PW-Co\textsubscript{3}N are all located between those of Co and CoO, indicating the average valence of Co should be between Co–O bond and Co–O bond, which is in accordance with the XPS Co 2p results. In the Fourier transform (FT) of the Co K-edge EXAFS spectra (Fig. 3b), there are two typical peaks corresponding to Co–N (\textsim 1.3 Å) and Co–Co (\textsim 2.3 Å) bonds and the intensity of Co–Co peak decreases obviously in PW-Co\textsubscript{3}N compared to pure Co\textsubscript{3}N due to the P/W doping. We further performed FT-EXAFS fitting to acquire more information about the coordination environment of PW-Co\textsubscript{3}N and Co\textsubscript{3}N and the fitting results are summarized in Supplementary Table 1. Comparing with Co\textsubscript{3}N, the Co–Co coordination number in PW-Co\textsubscript{3}N increases while the Co-N coordination number decreases, suggesting that the doped W possibly substitutes Co site. Moreover, to more clearly detect the coordination environment in PW-Co\textsubscript{3}N and Co\textsubscript{3}N, we carried out wavelet transform (WT) of Co K-edge EXAFS oscillations due to the high resolution in both K and R spaces. From the WT contour plots of Co\textsubscript{3}N (Fig. 3c) and PW-Co\textsubscript{3}N (Fig. 3d), the typical Co–Co bond (centered at about 7.5 Å\textsuperscript{-1}) and Co–N bond (centered at about 5 Å\textsuperscript{-1}) are further confirmed. Figure 3e shows the W L\textsubscript{3}-edge XANES spectra for PW-Co\textsubscript{3}N, W foil and WO\textsubscript{3}, in which W foil and WO\textsubscript{3} are used as references. The three samples exhibit peaks at \textsim 1020 eV, where the intensity of PW-Co\textsubscript{3}N locates between W foil and WO\textsubscript{3}, indicating the successful doping of W. Besides, the FT of W L\textsubscript{3}-edge EXAFS spectra (Fig. 3f) declare completely different coordination environment of W in PW-Co\textsubscript{3}N compared

**Fig. 2** High-resolution XPS spectra and soft XANES of PW-Co\textsubscript{3}N NWA/NF and Co\textsubscript{3}N NWA/NF. High-resolution XPS spectra of (a) Co 2p, (b) N 1s, (c) W 4f, and (d) P 2p; soft XANES of (e) Co L-edge spectra; (f) N K-edge spectra.
to W foil and WO3. We also performed FT-EXAFS fitting to probe the coordination environment of doped W in PW-Co3N, as shown in Fig. 3g, the fitting results are summarized in Supplementary Table 1 as well. The peaks at around 2.55 and 2.80 Å could be assigned to W-Co bond. The FT-EXAFS fitting results confirm that the doped W substitutes Co site and bonds with P and N. Moreover, the WT of W L3-edge contour plots of PW-Co3N (Fig. 3h) exhibit the typical W-Co bond (centered at about 7.5 Å) and Co-N bond (centered at about 6.0 Å−1), which further supports that W substitutes Co site.

Investigation of electrocatalytic HzOR and HER activities. The electrocatalytic HzOR activity is evaluated in a typical three-electrode configuration using Hg/HgO (containing 1.0 M KOH solution) as reference electrode and graphite rod as the counter electrode in 1.0 M of KOH/0.1 M of N2H4 electrolyte. The optimal doping level and annealing temperatures for PW-Co3N NWA/NF are firstly examined (Supplementary Figs. 8, 9), where it is confirmed that the sample obtained with the addition of 0.008 mmol PW12 and annealed at 420 °C exhibits the best catalytic activity. We also prepared W-Co3N NWA/NF and P-Co3N NWA/NF as control samples (Supplementary Figs. 10–15) to investigate the role of co-doping. Figure 4a displays the comparing linear sweep voltammetry (LSV) curves of PW-Co3N NWA/NF, W-Co3N NWA/NF, P-Co3N NWA/NF, Co3N NWA/NF, PW-Co-precursor/NF, bare Ni foam and Pt/C with the N2H4 concentration of 0.1 M, which can intuitively indicate the much better electrocatalytic activity of PW-Co3N NWA/NF compared with others. Specifically, the PW-Co3N NWA/NF requires ultralow working potentials of −55, 27, and 127 mV to achieve anodic current density of 10, 200, and 600 mA cm−2, which is far more excellent than that of sole doped W-Co3N NWA/NF, P-Co3N NWA/NF and un-doped Co3N NWA/NF, declaring the indispensability of dual doping. Also, our material PW-Co3N NWA/NF outperforms most of the reported materials, such as Cu1Ni2-N (0.5 mV at 10 mA cm−2)8, FeCo2 (129 mV at 100 mA cm−2)15, Ni2P/Ni foam (−25 mV at 50 mA cm−2)16 and Ni2P/Ni foam (100 mV at 172 mA cm−2)17, which are also summarized in Supplementary Table 2. The corresponding Tafel plots (Fig. 4b) indicates that the Tafel slope of PW-Co3N NWA is only 14 mV dec−1, which is much lower than that of W-Co3N NWA/NF (22 mV dec−1), P-Co3N NWA/NF (26 mV dec−1), Co3N NWA/NF (20 mV dec−1), Pt/C (37 mV dec−1), PW-Co-precursor/NF (120 mV dec−1) and bare Ni foam (77 mV dec−1), suggesting the most favorable catalytic kinetics towards HzOR. In order to check the intrinsic nature of the catalytic activity for PW-Co3N NWA/NF towards HzOR, the LSV curves with different
different concentrations of hydrazine, NWA/NF, W-Co3N NWA/NF, P-Co3N NWA/NF, Co3N NWA/NF, bare Ni foam, PW-Co-precursor and Pt/C; much lower than that of Co3N NWA/NF (2.88 \times 10^{-2} \Omega h), where 92.3% current retention can be observed (Fig. 4f).

It can be seen that a small overpotential of 41 mV is required to achieve 10 mA cm\(^{-2}\), which is only 9 mV larger than that of Pt/C (32 mV) and lower than recent reported transition-metal-nitride-based HER catalysts, such as NiCoN/C nanocages (103 mV)\(^{27}\), Co-Ni\(_3\)N (194 mV)\(^{42}\), Ni\(_2\)N/C (64 mV)\(^{43}\) and NiMo/NF (56 mV)\(^{44}\) (see details in Supplementary Table 3). The surface area is an important factor to affect the catalytic activity, we then measured the electrochemical double-layer capacitance (C\(_{dl}\)) of different materials to compare the electrochemical surface areas (Supplementary Fig. 19). The measured C\(_{dl}\) values are 70.0, 46.6, 26.2, 31.4, 1.3, 1.0, and 48.3 mF cm\(^{-2}\) for PW-Co3N NWA/NF, W-Co3N NWA/NF, P-Co3N NWA/NF, Co3N NWA/NF, Ni foam, PW-Co-precursor and Pt/C, respectively, implying the maximum numbers of accessible active sites owned by PW-Co3N NWA/NF. In order to evaluate the kinetic behavior, we further analyze the corresponding Tafel plots (Fig. 5b), where a much smaller Tafel slope of 40 mV dec\(^{-1}\) can be observed compared to that of W-Co3N NWA/NF (40 mV dec\(^{-1}\)), P-Co3N NWA/NF (143 mV dec\(^{-1}\)), Co3N NWA/NF (56 mV dec\(^{-1}\)), PW-Co-precursor (103 mV dec\(^{-1}\)) and bare Ni foam (118 mV dec\(^{-1}\)), and the value was even close to Pt/C (31 mV dec\(^{-1}\)). To better understand the interfacial charge transfer kinetics, the EIS measurement was conducted to obtain the Nyquist plots (Supplementary Fig. 20), where the PW-Co3N NWA/NF electrode exhibits the smallest charge transfer resistance (R\(_{ct}\)) of 2.2 \Omega compared to that of control samples, revealing the most excellent interfacial electron transfer kinetics during HER process. Figure 5c indicates the comparing LSV curves between those after continuous CV test and original one, where the same overpotential of 41 mV at 10 mA cm\(^{-2}\) can be observed after 5000 cycles, demonstrating the remarkable stability. Besides, the corresponding charge-transfer resistances (R\(_{ct}\)) shows ignorable changes (the inset of Fig. 5c), implying the structural robustness of the integrated electrode. Furthermore, the PW-Co3N NWA/NF also exhibits outstanding long-term durability evaluated by the chronoamperometric test recorded at working potential of \(-40\) mV.
for 25 h at the overpotential of 92 mV (Fig. 5d), where negligible decay can be observed, indicating its high stability for HER. In order to exclude the possible contribution of nickel compounds coming from Ni foam, the control sample by annealing Ni foam with sodium hypophosphite at 420 °C under NH3 (denoted as PN/NF) was synthesized (Supplementary Fig. 21) and its electrocatalytic performance is investigated (Supplementary Table 4), but also exhibits favorable kinetics. The results proved that our OHzS system not only needs less electric energy in practical use (see more information in Supplementary Table 5). As a proof-of-concept, the self-powered H2 production system is demonstrated by powering the OHzS electrolyzer using the DHzFC with typical images shown in Supplementary Movie 1. The H2 yield by this system is measured using gas chromatography, as shown in Fig. 7e. It can be calculated that a decent H2 production rate of 1.25 mmol h⁻¹ can be achieved at room temperature, which is competitive among the reported values from self-powered H2 production systems, demonstrating the exciting potential for highly efficient H2 productions. Moreover, the total efficiency (TE) from hydrazine to H2 of this self-power system is calculated to be about 45.8%, which is comparable to other hydrogen generation systems.

**Demonstration of self-powered H2 production.** In order to further demonstrate the possible applications of our catalyst, we built a self-powered system by integrating a direct hydrazine fuel cell (DHzFC) using PW-Co3N NWA/NF anode and commercial Pt/C cathode to drive OHzS for H2 production, which can be schematically illustrated in Fig. 7a. The room temperature performance of the DHzFC shows an open-circuit voltage (OCV) of 0.98 V (Supplementary Fig. 23) and can reach a maximum power density of 46.3 mW cm⁻² at a cell voltage of 0.429 V (Fig. 7b), which is comparable with the recently reported values under similar working conditions, which is also summarized in Supplementary Table 5. As a proof-of-concept, the self-powered H2 production system is demonstrated by powering the OHzS electrolyzer using the DHzFC with typical images shown in Fig. 7c, d, where vigorous gas evolution can be observed (Supplementary Movie 1). The H2 yield by this system is measured using gas chromatography, as shown in Fig. 7e. It can be calculated that a decent H2 production rate of 1.25 mmol h⁻¹ can be achieved at room temperature, which is competitive among the reported values from self-powered H2 production systems, demonstrating the exciting potential for highly efficient H2 productions. Moreover, the total efficiency (TE) from hydrazine to H2 of this self-power system is calculated to be about 45.8%, which is comparable to other hydrogen generation system
Compared with gaseous hydrogen or carbon monoxide, hydrazine has the advantage of more convenient transportation and storage as a liquid fuel at ordinary temperatures. However, it is necessary to state that hydrazine is a highly toxic chemical, which may be a challenging issue for the large-scale applications. This is also the major reason that we choose to build our self-powered system working at room temperature and low hydrazine concentration. In order to tackle this obstacle, Asazawa et al. designed a detoxification technique to fix the hydrazine as the carbonyl groups in the harmless, stable and recyclable polymer for storage, which can be released using water or KOH (aq) when needed. This strategy has been considered as one of the promising strategies for large-scale applications involving toxic hydrazine.

Discussion

To further recognize the HzOR-active species, we conducted the in situ Raman spectroscopy measurements of PW-Co3N NWA/NF to obtain real-time detection, as shown in Supplementary Fig. 25. There are two peaks located at 682 and 520 cm⁻¹ for our pristine PW-Co3N NWA/NF, which is consistent with previous reports. When the applied potential increased till 0.8 V vs. RHE, the peaks of PW-Co3N NWA/NF remained constant, which implied that there was no visible surface change during the HzOR process within the measured potential range. The comparing XRD patterns (Supplementary Fig. 25b) of the samples before and after the long-term stability test further confirmed the unchanged phase. Notably, when the potential increased to 1.7 V vs. RHE, at which the OER process should happen, the original peaks disappeared and the emerging broad peak at the range of 500–600 cm⁻¹ could be assigned to the conversion of metal nitride to metal oxyhydroxide (from Co3N to CoOOH in our case), which has been broadly observed in previous reports regarding the OER electrocatalysis process. Therefore, it can be concluded that the metal nitride itself could act as the active species for HzOR without observable surface change during the catalytic process.

In order to unravel the possible origin of the better performance after P/W co-doping, the DFT calculations are then applied for both HER and HzOR. Combined with the theoretical calculation and the experimental result regarding the structural stability after doping, it is reasonable to use the model where the surface Co atoms in Co3N are replaced by W atoms and subsurface N atoms are replaced by P atoms, as indicated in Fig. 8a–d, Supplementary Fig. 26 and Supplementary Note 2. It has been generally demonstrated that the HER process can be described with three states including an initial pair of H⁺ and e⁻, an intermediate of adsorbed H (H*) and the final product of 1/2 H₂, as shown in Fig. 8e. As the critical descriptor, the free energy of hydrogen absorption (ΔGH*) of PW-Co3N is calculated to be −0.41 eV, which is closer to the thermoneutral value than that of the pure Co3N (−0.52 eV). This could imply the facilitated hydrogen adsorption/desorption behavior upon P/W doping, which is consistent with better HER activity of PW-Co3N NWA/NF. In order to understand the fact that the ΔGH* of PW-Co3N is

Fig. 6 Electrochemical performance of OHzS using PW-Co3N NWA/NF without DHzFC. a Comparison of LSV curves for OHzS in 1.0 M KOH/0.1 M hydrazine and OWS in 1.0 M KOH using PW-Co3N NWA/NF as both the anode and cathode, b Comparison of the overpotentials required to reach different current densities for OHzS and OWS, c The amount of hydrogen theoretically calculated and experimental measured for OHzS, d The amount of hydrogen theoretically calculated and experimental measured for OWS, e J-t curve of OHzS recorded at 98 mV for 20 h.
far more negative compared to benchmark Pt (−0.10 eV) while their HER catalytic activity is almost the same, we further conducted DFT calculations on d-band center analysis, the water absorption energy (ΔE_{abs}) and charge difference analysis. As shown in Fig. 8f, the d-band center of pure Co3N (−1.41 eV) notably shifts down to (−1.54 eV) after P/W co-doping, which clearly demonstrates that hydrogen desorption is promoted besides the decreasing of hydrogen adsorption energy. In addition, ΔE_{abs} on Co3N (001) and PW-Co3N (001) are −0.31 and −0.56 eV (Fig. 8g), which indicates that the adsorption of H2O molecule is energetically more favorable on the PW-Co3N surface. These results suggest that the P/W doping can not only manipulate the hydrogen absorption energy, but also tailor the d-band center and facilitate the absorption of H2O, which can synergistically promote the HER activity. We further performed the charge density difference plot of PW-Co3N, as shown in Fig. 8h and i. As can be seen, the charge redistribution is dominantly restricted on P/W and their nearest neighboring Co/N, and the doped W and nearby Co sites possess charge depletion while P and the neighboring N possess charge accumulation. This electron localization behavior upon doping could contribute to the enhanced catalytic activity of PW-Co3N.

The theoretical deciphering of HzOR process is more important since its investigation is relatively rare compared to that of HER process. Therefore, DFT calculations on the free energy of N2H4 adsorption (ΔG_{N2H4}) and each dehydrogenation step from adsorbed NH2NH2+ to N2 on the Co site of the (001) surface of Co3N and PW-Co3N with Co-termination are further conducted, as shown in Supplementary Fig. 27 and Fig. 8j. Supplementary Fig. 27 exhibited two different unit cells of Co3N, i.e., Co-terminated and N-terminated. The distance between N2H4 molecular and the nearest neighboring N atom is 5.39 Å, which is much larger than the distance of 1.98 Å between N2H4 and Co atom. This means that the N atom terminated unit cell is not favorable for N2H4 adsorption, which is inconsistent with our experimental results. Therefore, we adopted the Co-termination unit cell as the model for DFT calculation. As indicated, the PW-Co3N exhibits a more negative ΔG_{N2H4} of −1.12 eV compared to that of Co3N (−0.35 eV), suggesting the more favorable N2H4 adsorption, which is undoubtedly important for the further catalytic oxidation process. More importantly, based on the calculation results on the comparison of free-energy changes of each dehydrogenation step for both Co3N and PW-Co3N (Fig. 8j), it can be concluded that the dehydrogenation of *NH2NH to *N3H is the potential determining step (PDS) for Co3N towards HzOR, while the PDS for PW-Co3N is the desorption process of *N3 to N2. As indicated, a much higher ΔG value of +0.7 eV is obtained for pure Co3N, while it is only +0.5 eV for PW-Co3N. These results demonstrate that the introduction of P and W could largely optimize electronic structure of Co3N, hence facilitates the thermodynamic behavior of both hydrogen adsorption in HER and dehydrogenation process in HzOR.

In summary, we have demonstrated that the integrated electrode composed of P, W co-doped Co3N nanowire arrays grown on Ni foam (denoted as PW-Co3N NWA/NF) possesses benchmark electrocatalytic activity toward both HzOR and HER. Specifically, it can achieve 10, 200, and 600 mA cm−2 with ultralow working potential of −55, 27, and 127 mV (vs. RHE) for HzOR in 1.0 M KOH/0.1 M N2H4 electrolyte. The PW-Co3N/NF also exhibits Pt-like activity for HER with a low overpotential of 41 mV at 10 mA cm−2 and a small Tafel slope of 40 mV dec−1 in 1.0 M KOH electrolyte. Importantly, with the built two-electrode electrolyzer using PW-Co3N NWA/NF as both anode and cathode catalysts for overall hydrazine splitting (OHZS), only an operation voltage of 28 mV is needed to achieve the current density of 10 mA cm−2, and only 277 mV is required to reach 200 mA cm−2, which is superior compared to state-of-the-art...
values. Furthermore, as a proof-of-concept, the self-powered H\textsubscript{2} production system is demonstrated by using a homemade direct hydrazine fuel cell (DHzFC) to drive OHzS with hydrazine as the sole liquid fuel. The DFT calculations provide the fundamental origins of the enhanced HzOR and HER performance, in which the P/W doping can not only decrease the free energy of the PDS, but also make the dehydrogenation of NNH\textsuperscript{+} to NNH\textsuperscript{+} more thermoneutral.

**Methods**

**Chemical and materials.** Cobalt nitrate hexahydrate (Co(NO\textsubscript{3})\textsubscript{2}·6H\textsubscript{2}O), urea, ammonium fluoride (NH\textsubscript{4}F), sodium tungstate dihydrate, sodium hypophosphite and phosphotungstic acid hydrate (H\textsubscript{3}PW\textsubscript{12}O\textsubscript{40}·(NO\textsubscript{3})\textsubscript{2}·6H\textsubscript{2}O, 10.0 mmol of urea, 4.0 mmol of NH\textsubscript{4}F and 0.008 mmol of PW\textsubscript{12} are purchased from Aladdin Industrial Corporation. All of the chemicals were used directly without further purification.

**Synthesis of PW-Co\textsubscript{3}N NWA/NF.** The PW-Co\textsubscript{3}N nanowire arrays are synthesized via a simple two-step method. In a typical synthesis, 1.9 mmol of Co(NO\textsubscript{3})\textsubscript{2}·6H\textsubscript{2}O, 10.0 mmol of urea, 4.0 mmol of NH\textsubscript{4}F and 0.008 mmol of PW\textsubscript{12} are dissolved in 40 mL of deionized water, firstly. The as-obtained solution is continuously stirred to achieve the uniform dispersion and then transferred into a furnace. A piece of Ni foam (3 cm × 2 cm) is pretreated with 3.0 M of HCl to remove the possible oxidation layer and impurity on the surface, and then washed with DI water and ethanol for several times. After cooling to room temperature, the as-obtained PW-Co-precursor grown on the Ni foam is subsequently immersed into the autoclave and heated at 120 °C for 10 h. Then, the cleaned nickel foam is taken out and washed with DI water and ethanol before use. Then, the cleaned nickel foam is subsequently immersed into the autoclave and heated at 120 °C for 10 h. After cooling to room temperature, the as-obtained PW-Co-precursor grown on nickel foam is took out and washed with DI water and ethanol for several times. The final PW-Co\textsubscript{3}N nanowire arrays can be obtained by the thermal nitridation process at 420 °C for 2 h under NH\textsubscript{3} atmosphere. The doping level can be easily adjusted by simply changing the added amount of PW\textsubscript{12} while keeping other conditions identical. The W-Co\textsubscript{3}N NWA/NF was prepared under the same synthesis route except replacing PW\textsubscript{12} by sodium tungstate dihydrate with the same added amount of 0.1 mmol for tungsten. Besides, P-Co\textsubscript{3}N NWA/NF was synthesized by the conventional vapor phosphorization method at 300 °C under Ar atmosphere using a spot of sodium hypophosphite as the doping agent (5 mg sodium hypophosphite and a piece of 2 cm\textsuperscript{3} 3 cm as-prepared Co\textsubscript{3}N NWA/NF).

**Materials characterization.** The morphology characterization was tested by field-emission scanning electron microscopy (FESEM, ESEM-6700F, SU-8200, Sirion200) and transmission electron microscopy (TEM, JOEL, JEM-2010, JEM-ARM200F, HT-7700). The powder X-ray diffractogram (XRD, TTR-III, Japan) was used for analyzing the crystal structure of as-obtained samples. Valence state of element of the samples were obtained by X-ray photoelectron spectroscopy (XPS, ESCALAB 250). The soft XANES (Co L-edge and N K-edge spectra) were performed on Photoemission Endstations (BL10B) in National Synchrotron Radiation Laboratory.

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**Fig. 8 DFT calculated profiles of free energy.** Top- and side-view of atomic structure models for (a, c) Co\textsubscript{3}N; (b, d) PW-Co\textsubscript{3}N; (e) The free-energy diagram of HER at the equilibrium potential for Co\textsubscript{3}N and PW-Co\textsubscript{3}N, H\textsuperscript{+} denotes that intermediate adsorbed hydrogen; (f) The d band of density of states (DOS) of Co\textsubscript{3}N and PW-Co\textsubscript{3}N; (g) Water adsorption energy on Co\textsubscript{3}N and PW-Co\textsubscript{3}N. Top-(h) and side-(i) view of charge density difference analysis for PW-Co\textsubscript{3}N with the cyan region representing charge depletion and the yellow region representing charge accumulation. The isosurface value is 0.012 eÅ\textsuperscript{−2}; (j) The free-energy profiles of HzOR on the Co\textsubscript{3}N and PW-Co\textsubscript{3}N surfaces. The inset in (j) are the most stable configurations of the each adsorbed intermediate on the Co site.
membranes were used as the solid electrolyte and the anodes were the PW-Co3N2 surface unit cell with Co-termination. Four of the surface Co atoms are sub-

H2 molecule. Thus the reaction Gibbs free energies can be calculated with eqs:67

\[
\Delta G_{fi} = \Delta G_{\text{N}2,\text{H}4} + 0.5 \Delta G_{\text{H}2} - \Delta G_{\text{N}2 \text{H}4,\text{H}2} - eV - kT \ln(1 - \exp(-eV/kT)) \]

(13)

Among which \( R = 8.314 \) J mol\(^{-1}\) K\(^{-1} \), \( T = 298.15 \) K, \( h = 6.63 \times 10^{-34} \) J s, \( k_B = 1.38 \times 10^{-23} \) J K\(^{-1} \); \( i \) is the frequency number, \( \nu \) is the vibrational frequency (unit is cm\(^{-1} \)).

**Data availability**

The authors declare that the main data that support the findings of this study are included within the article and Supplementary Information part. Extra data are available from the corresponding author upon reasonable request.

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Additional information

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