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A defective NiCo-pentlandite/black phosphorus heterostructure for efficient water splitting electrocatalysis†

Hang Liu,^{‡a} Yahui Tian,^{‡b} Syama Lenus,^a Xin Zhao,^a Zhengfei Dai^a and
Tingting Liang^{‡*ac}

Herein, we report a nickel cobalt pentlandite/black phosphorus (Ni–Co₉S₈/BP) heterostructure as a bifunctional electrocatalyst, i.e., Ni doped Co₉S₈ vertically grown on the surface of black phosphorus. The nanoporous network heterostructure and surface sulfur vacancies endow Ni–Co₉S₈/BP with more active sites and accelerated reaction kinetics, thus realizing a low potential of 1.65 V at 10 mA cm^{−2} for water splitting, which outperforms most Co₉S₈-based electrocatalysts.

Electrochemical water electrolysis (EWS) is considered as a promising, environmentally friendly, and effective approach to generate hydrogen with high purity, which consists of the hydrogen evolution reaction (HER) at the cathode and the oxygen evolution reaction (OER) at the anode.^{1–3} In the past few decades, noble metal-based materials (e.g., Pt-based ones for the HER and Ir- or Ru-based ones for the OER) are widely regarded as activity references for EWS, but these catalysts suffer from their scarcity and limited sustainability for large-scale production.^{4,5} Hence, developing earth-abundant and non-precious transition metal-based catalysts as alternatives is of great importance for the widespread commercialization and renewable acceleration of hydrogen energy.^{6–8} Among a great number of transition metal-based catalysts, transition metal sulphide (TMS) compounds have aroused tremendous attention due to their variant 3d-valence electrons and favourable electrical conductivity for boosting the HER and OER processes.^{9–12} In this case, nanostructured cobalt sulphides are emerging as appealing bifunctional electrocatalysts for EWS by virtue of their excellent catalytic

properties (e.g., low water dissociation energy and enriched active sites) and remarkable electrochemical stability.^{13–16} For example, Ma *et al.* synthesized Co₉S₈ hollow spheres (HSs) as bifunctional catalysts with low overpotentials of 267 mV (HER) and 342 mV (OER) at a current density of 10 mA cm^{−2} in alkaline electrolyte.¹⁷ Despite much progress having been achieved so far, further improvement in the electrocatalytic properties of cobalt sulphides is still very demanded.

An applicable strategy is cation valence engineering through metal heteroatom doping.^{2,18} The existence of metal heteroatoms at the interface of the electrocatalyst can enhance the intrinsic electrocatalytic activity by tuning the surface electronic states and the electron donating/accepting behaviors.^{6,19} A recent work demonstrated that the prepared Co₃S₄ nanowires with doping a small amount of Ni show a lower HER overpotential of 199 mV at 10 mA cm^{−2} when compared to pristine Co₃S₄ (218 mV at 10 mA cm^{−2}).¹⁸ Another practical strategy to improve the EWS performance is the intrinsic defect construction on the nanostructured cobalt sulphide.^{20,21} It has been proven that the S vacancy (V_s) is capable of promoting the electron mobility and maximizing the active sites due to the low number of coordination bonds.^{22–24} Zhu *et al.* reported that CoS_{0.61}Se_{0.25} HSs with V_s were synthesized by Se heteroatom substitution, in which a low overpotential of 108 mV at 10 mA cm^{−2} for the HER was delivered.²⁴ Besides, a rapid interfacial charge transfer over electrocatalysts is also elementary for an efficient EWS process.²⁵ Hybridizing active catalysts with other conductive materials is normally noticed as a beneficial route to promote the EWS performance.^{26–30} Owing to their unique electronic characteristics (e.g., a high carrier mobility of ~1000 cm² V^{−1} s^{−1}, adjustable bandgap, *etc.*) and high hydrophilicity, p-type black phosphorus (BP) lamellae can be promising conductive candidates to host cobalt sulphide-based catalysts, since the injection effect of oxidative holes would further facilitate the OER process.^{25,31} Bearing the above-mentioned strategies in mind, it is thus expected that designing BP-hosted cobalt sulphide coupled with metal doping and S vacancies as the

^a State Key Laboratory for Mechanical Behavior of Materials, Xi'an Jiaotong University, Xi'an 710049, China. E-mail: liangtingting@haust.edu.cn

^b Institute of Physical Science and Information Technology, Anhui University, Hefei, 230601, China

^c School of Materials Science and Engineering, Henan University of Science and Technology, Luoyang, 471023, China

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‡ These authors contributed equally to this work.

bifunctional water splitting electrocatalyst can be an appropriate option for high-performance EWS.

In this communication, we have fabricated a NiCo-pentlandite/black phosphorus heterostructure (Ni-Co₉S₈/BP) with S vacancies to realize highly active and durable water electrolysis. For the preparation of Ni-Co₉S₈/BP, NiCo hydroxide nanosheets were initially grown *in situ* vertically on few-layer BP, followed by one-step sulfurization. The as-prepared nanostructured heterostructure exhibits excellent electrocatalytic performance for both alkaline HER and OER with small overpotentials (η_{10} , at 10 mA cm⁻²) of 160 mV and 258 mV, respectively. The water electrolyser assembled with Ni-Co₉S₈/BP displays a low potential of 1.65 V at 10 mA cm⁻² with long-term stability. The experimental investigations of the Ni-Co₉S₈/BP heterostructure have unveiled that, compared to its counterparts, the increased ratio of Ni³⁺/Ni²⁺ and the generated S vacancies play electron-accepting roles, and the reduced ratio of Co³⁺/Co²⁺ possesses the electron-donating character for promoting the OER and HER processes, respectively. Research sheds light on valence engineering and vacancy modulation in BP-based heterostructure electrocatalysts.

The synthesis process of the Ni-Co₉S₈/BP heterostructure is shown in Fig. 1a. The bulk BP crystal was first electro-exfoliated into BP lamellae *via* a two-electrode equipment in an electrolyte, as we previously reported.^{6,32} Then, Ni-Co(OH)₂ was loaded on the BP lamellae to form the interface of Ni-Co(OH)₂/BP through the wet-chemical synthesis and subsequent annealing process, which was determined by XRD after comparison with the standard diffraction patterns (Fig. S1a, ESI†). The SEM (Fig. 1b) and TEM images (Fig. S1b and c, ESI†) of Ni-Co(OH)₂/BP both confirm that Ni-Co(OH)₂ nanosheets grow vertically on the BP lamellae, forming a nanoporous network heterostructure. The as-prepared Ni-Co(OH)₂/BP was finally forwarded to the Ni-Co₉S₈/BP heterostructure by one-step sulfurization. The SEM and TEM

images of Ni-Co₉S₈/BP show that the as-formed heterostructure still maintains the porous morphology as displayed in Fig. 1c and Fig. S2a (ESI†), which could possibly benefit gas dissipation and exposure of the active-edge sites of Ni-Co₉S₈ for promoting the water-electrolytic kinetic process. The HRTEM image of Ni-Co₉S₈/BP is also displayed in Fig. 1d. It illustrates lattice fringes with spacings of 0.525 nm and 0.286 nm, corresponding to the (020) plane of BP and the (222) plane of Co₉S₈, respectively. Furthermore, the SAED images in Fig. 1e indicate the (040) lattice plane of BP and the (111)/(420) planes of Co₉S₈, respectively. The elemental mappings (Fig. S2b, ESI†) confirm the uniform distributions of P, Co, Ni and S in the Ni-Co₉S₈/BP heterostructure. Fig. 1f presents the XRD pattern of the Ni-Co₉S₈/BP heterostructure along with that of Co₉S₈/BP. The main peaks of Ni-Co₉S₈/BP located at 29.67°, 31.06°, 47.89° and 51.97° correspond to the (311), (222), (511) and (440) crystal planes of Co₉S₈ (JCPDS No. 86-2273).³³ The other peaks of Ni-Co₉S₈/BP at 33.87° and 35.00° are in accordance with the (040) and (111) planes of BP (JCPDS No. 73-1358).³⁴ As for references, the SEM images of Co(OH)₂, Ni-Co(OH)₂, Co(OH)₂/BP, Co₉S₈, Ni-Co₉S₈, and Co₉S₈/BP are also provided in Fig. S3 (ESI†).

Afterwards, the chemical valence and compositions of different samples were investigated by XPS as shown in Fig. 2a–c and Fig. S4 (ESI†). The deconvolution of Co 2p XPS spectra is displayed in Fig. 2a. Two sets of doublets are assigned to Co 2p_{3/2} (779 eV, Co³⁺; 781.5 eV, Co²⁺) and Co 2p_{1/2} (794.1 eV, Co³⁺; 797.4 eV, Co²⁺), respectively.³⁵ The Ni 2p XPS spectra in Fig. 2b show that two sets of doublets correspond to Ni 2p_{3/2} (854.2 eV,

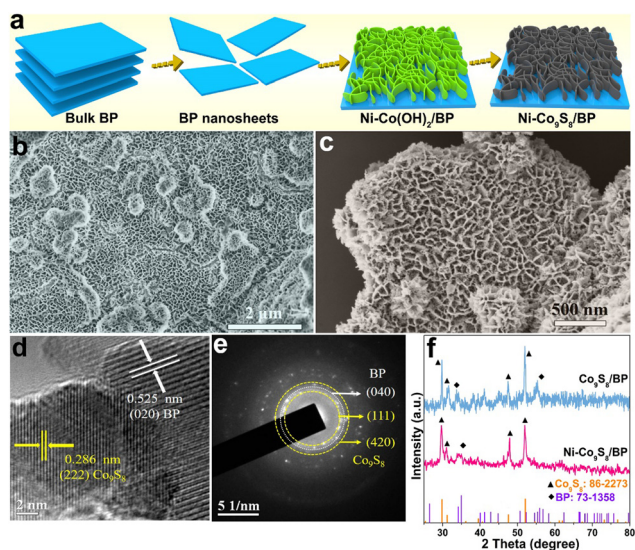


Fig. 1 (a) Synthesis diagram of the Ni-Co₉S₈/BP heterostructure. SEM images of (b) Ni-Co(OH)₂/BP and (c) Ni-Co₉S₈/BP. (d) HRTEM and (e) SAED images of Ni-Co₉S₈/BP. (f) XRD patterns of Co₉S₈/BP and Ni-Co₉S₈/BP, respectively.

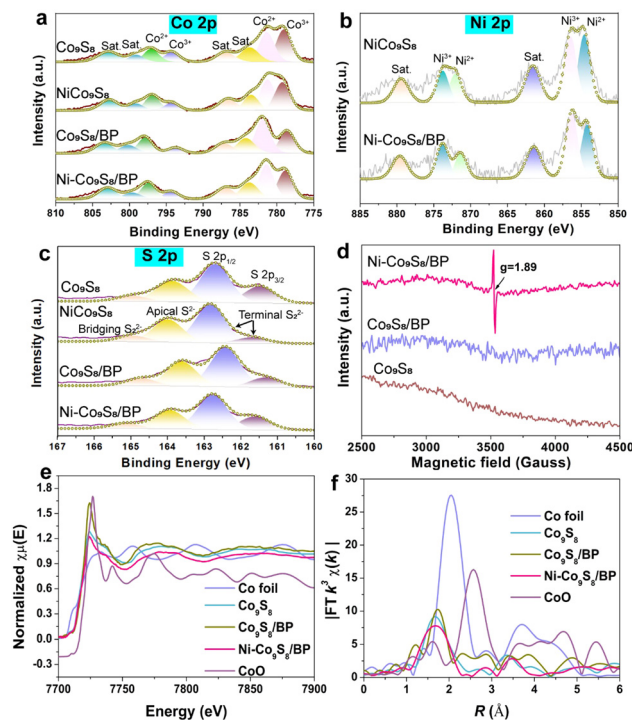


Fig. 2 (a)–(c) High-resolution Co 2p, Ni 2p and S 2p XPS spectra of the relevant samples. (d) EPR spectra of Co₉S₈, Ni-Co₉S₈, and Co₉S₈/BP, respectively. (e) XANES and (f) EXAFS spectra of Co, CoO, Co₉S₈, Co₉S₈/BP and Ni-Co₉S₈/BP, respectively.



Ni²⁺; 856.4 eV, Ni³⁺) and Ni 2p_{1/2} (871.2 eV, Ni²⁺; 873.8 eV, Ni³⁺).³⁶ It is revealed that the valence states of Ni-Co₉S₈/BP are reconstructed due to the increased ratio of Ni³⁺/Ni²⁺ and the reduced ratio of Co³⁺/Co²⁺ after Ni doping and BP hosting, undertaking both electron-accepting and electron-donating characters for enhancing the HER and OER. The S 2p spectra in Fig. 2c present S 2p_{1/2} (162.7 eV), S 2p_{3/2} (161.5 eV), apical S²⁻ (163.9 eV) and bridging S₂²⁻ (165 eV).⁶ The P 2p spectra in Fig. S4b (ESI†) shows that a set of doublets located in the range of ~128–132 eV are regarded to P 2p_{3/2} and P 2p_{1/2}, respectively.⁶ A peak at a higher binding energy is generally considered as P–O bonding.³⁴ When compared to Co₉S₈ and Co₉S₈/BP, the EPR signal intensity of Ni-Co₉S₈/BP can be observed at a *g*-factor of 1.89, which is attributed to the presence of V_s upon Ni doping (Fig. 2d).³⁷ Thus, it can be deduced that the nanoscale Kirkendall effect takes place in the transformation of Ni-Co(OH)₂/BP to Ni-Co₉S₈/BP during the subsequent sulfurization process.³⁸ The unbalanced diffusion rates between the rapid outward diffusion of the Ni atom from the Ni-Co(OH)₂ nanosheet and the slow inward pervasion of S atoms from sulphur powder result in V_s formation within the nanosheet. The V_s with a high electron-accepting capacity can be also regarded as active sites for the OER.³⁹

Besides, the surface area and pore structure of the Ni-Co₉S₈/BP sample were studied based on the N₂ adsorption/desorption isotherms, as shown in Fig. S5 (ESI†). It gives a type-IV isotherm with a typical H3-type hysteresis loop, demonstrating a mesoporous structure.^{40,41} Ni-Co₉S₈/BP has a high BET specific surface area of 153.18 m² g⁻¹, which is much higher than those of the other representative reference samples (*e.g.*, Ni-Co₉S₈, 15.90 m² g⁻¹; Ni-Co(OH)₂/BP, 19.41 m² g⁻¹; Ni-Co(OH)₂, 3.64 m² g⁻¹). The high BET surface area of Ni-Co₉S₈/BP is further capable of boosting its electrocatalytic activity since more active sites are exposed during the catalytic reactions.⁴² The coordination environment and chemical state of Ni-Co₉S₈/BP were then investigated by XANES and EXAFS spectroscopies. Fig. 2e shows the Co K-edge XANES spectra of the relevant samples. Compared to Co₉S₈ and Co₉S₈/BP, the Co K-edge spectrum of Ni-Co₉S₈/BP has a gradual shift to lower energies, confirming the change in the Co state from Co³⁺ to Co²⁺.³⁹ The position of the absorption edge for Ni-Co₉S₈/BP is between Co foil and Co₉S₈/BP, much closer to Co₉S₈/BP. Therefore, this characteristic indicates Co²⁺ is the major valence state of Co in Ni-Co₉S₈/BP, which is well consistent with the XPS analyses in Fig. 2a.⁴³ In Fig. 2f, the Co K-edge Fourier-transform (FT) EXAFS spectrum of Ni-Co₉S₈/BP displays a peak at ~1.69 Å, which corresponds to the Co–S bonding environment. Compared to the peak at 1.72 Å in the spectrum of Co₉S₈/BP, the lower value of Ni-Co₉S₈/BP indicates the shorter electron-transfer path in Ni-Co₉S₈/BP.⁴⁴

To investigate the HER electrocatalytic properties, LSV curves were tested after 50 cycles of stabilization (Fig. 3a). Ni-Co₉S₈/BP shows a η_{10} overpotential of 121 mV in 0.5 M H₂SO₄, which is much lower than those of Co₉S₈/BP (202 mV), Ni-Co₉S₈ (218 mV), Co₉S₈ (218 mV) and BP (403 mV). The corresponding Tafel slopes were calculated and are presented in Fig. S6a (ESI†), where all the Tafel slopes of the catalysts, except for BP, are

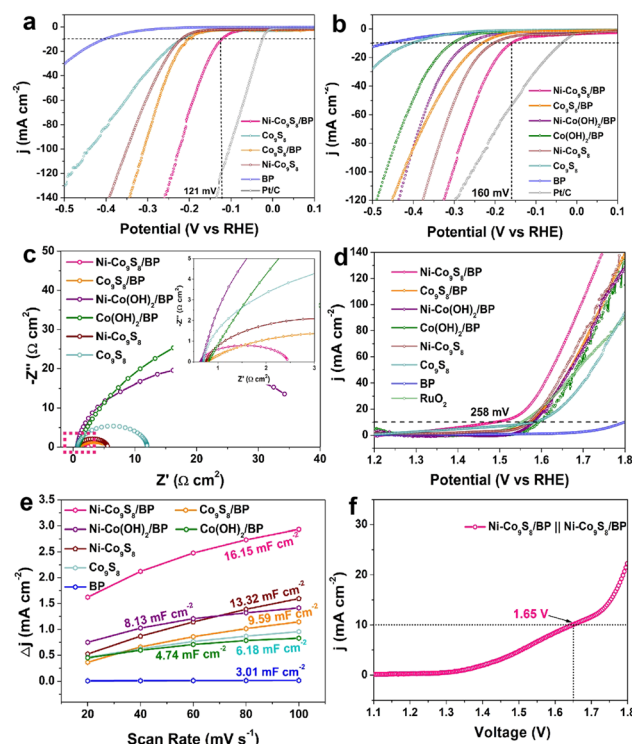
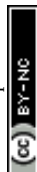


Fig. 3 HER polarization curves of relevant samples in (a) 0.5 M H₂SO₄ and (b) 1 M KOH, respectively. (c) EIS spectra (the inset shows the enlarged area of the pink dotted line). (d) OER polarization curves of relevant samples in 1 M KOH. (e) Current–potential curves with different scan rates in 1 M KOH. (f) Polarization curves of overall water splitting based on the Ni-Co₉S₈/BP||Ni-Co₉S₈/BP couple.

lower than 118 mV dec⁻¹, indicating the rate-determining step (RDS) during the HER process is the Volmer step (H₃O + e⁻ → H_{ads}).⁶ Specifically, the Tafel slope for Ni-Co₉S₈/BP (76 mV dec⁻¹) is smaller than the values for Co₉S₈/BP (91 mV dec⁻¹), Ni-Co₉S₈ (101 mV dec⁻¹) and Co₉S₈ (101 mV dec⁻¹), illustrating that Ni-Co₉S₈/BP has the most favourable HER kinetics over the other reference electrocatalysts. The HER performance of Ni-Co₉S₈/BP in 1 M KOH was also measured and is shown in Fig. 3b and Fig. S6b (ESI†). The comparison of the reference samples and Ni-Co₉S₈/BP reveals a higher HER catalytic activity for the latter, featuring a smaller η_{10} overpotential of 160 mV and a smaller Tafel slope of 119 mV dec⁻¹. The values of η_{10} overpotentials and Tafel slopes found here are comparable or superior to those of the reported relevant catalysts in acidic and basic media (Table S1, ESI†). The electrochemical impedance spectroscopy (EIS) measurements further give additional insights into HER kinetics and interfacial properties (Fig. 3c). Nyquist plots show that Ni-Co₉S₈/BP has the smallest charge-transfer resistance among all the samples, which is in agreement with the superior catalytic activity of Ni-Co₉S₈/BP examined by LSV. To estimate the stability of Ni-Co₉S₈/BP, the chronopotentiometry tests were performed in both 1 M KOH and 0.5 M H₂SO₄, as shown in Fig. S6c and d (ESI†). The HER catalytic currents are sustainable with slight fluctuations after 24 h, indicating a high stability in both acidic and basic media.

The OER catalytic performance was also tested in 1 M KOH after 50 cycles of stabilization. Fig. 3d shows the LSV curves of



the samples, illustrating the catalytic properties of Ni-Co₉S₈/BP with a η_{10} overpotential of 258 mV, which is much lower than those of commercial RuO₂ (322 mV), Co₉S₈/BP (341 mV), Ni-Co(OH)₂/BP (351 mV), Co(OH)₂/BP (363 mV), Ni-Co₉S₈ (340 mV) and Co₉S₈ (352 mV). The η_{10} overpotential for Ni-Co₉S₈/BP is striking as compared to the other relevant OER catalysts listed in Table S2 (ESI[†]). In Fig. S6e (ESI[†]), analysis of the data gives a Tafel value of 118 mV dec⁻¹ for Ni-Co₉S₈/BP. To estimate the electrochemically active surface area (ECSA), the electrochemical double-layer capacitance (C_{dl}) at the solid-liquid interface was obtained through CV measurements at various scan rates (Fig. S7, ESI[†]). Compared to the other reference samples, the C_{dl} for Ni-Co₉S₈/BP shows a considerable increase with a value of 16.15 mF cm⁻² (Fig. 3e), suggesting the higher ECSA for the OER. As presented in Fig. S6f (ESI[†]), the chronopotentiometry measurement for Ni-Co₉S₈/BP was then carried out for 24 h, illustrating the good retention of OER catalytic activity. The structural characterization after the OER stability test was also checked and is shown in Fig. S8 (ESI[†]). The morphology of lamellae is well preserved and Ni-Co₉S₈/BP maintains its phases of Co₉S₈ and BP. The EDX maps confirm the elements of Ni-Co₉S₈/BP remain well after the OER stability test. Given its capabilities for both water oxidation and reduction, the Ni-Co₉S₈/BP catalysts were investigated for their overall water splitting (OWS) performance in 1.0 M KOH with a two-electrode setup. In order to achieve a water splitting current density of 10 mA cm⁻², a cell voltage of 1.65 V was needed for Ni-Co₉S₈/BP||Ni-Co₉S₈/BP electrolyzers, as shown in Fig. 3f. As a bifunctional electrocatalyst, the performance of Ni-Co₉S₈/BP for OWS is superior to the results reported for relevant bifunctional electrocatalysts (Table S3, ESI[†]). The durability of the Ni-Co₉S₈/BP||Ni-Co₉S₈/BP electrolyzers was examined in the long-term electrolysis experiment at a cell voltage of 1.65 V in 1.0 M KOH (Fig. S6g, ESI[†]). The water splitting current remained almost constant with only a slight degradation by the end of the electrolysis.

In summary, we have successfully developed a nickel-doped cobalt sulphide/black phosphorus heterostructure by growing NiCo hydroxide nanosheets on BP lamellae and subsequent one-step sulfurization for electrochemical water electrolysis. Based on the above-mentioned evidence, not only Ni³⁺/Ni²⁺ and Co³⁺/Co²⁺ pairs have been reconstructed, but also S vacancies have been generated after Ni doping and BP hosting in Ni-Co₉S₈/BP. The modulated Ni³⁺/Ni²⁺ and S vacancies play electron-accepting roles, while the tuned Co³⁺/Co²⁺ exhibits the electron-donating character for boosting the water splitting process. Thanks to the hetero-interface engineering and dual-modulation strategy (*i.e.*, Ni doping and S vacancy modulation), the as-synthesized Ni-Co₉S₈/BP heterostructure exhibits excellent electrocatalytic performance for both the HER (η_{10} overpotentials of 121 mV in 0.5 M H₂SO₄ and 160 mV in 1 M KOH) and OER (η_{10} overpotential of 258 mV in 1 M KOH). A two-electrode electrolyser with Ni-Co₉S₈/BP catalysts only needs 1.65 V at 10 mA cm⁻² for stable overall water splitting. This work opens a new avenue for designing advanced noble-metal-free electrocatalysts by co-engineering the interface and electronic structure.

Conflicts of interest

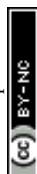
There are no conflicts to declare.

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