



Heterostructured Bi-Cu₂S Nanocrystals for Efficient CO₂ Electroreduction to Formate

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In this work, we report a simple colloidal route to synthesize a new class of heterostructures consisting of a *p*-block metal (Bi) and a transition metal chalcogenide (Cu₂S). During the synthesis, Bi nucleated first and served as seeds for the shaped-controlled epitaxial growth of Cu₂S nanorods. A new concept of the interfacial synergy between *p*-block metals and transition metal chalcogenide is also demonstrated. These heterostructured Bi-Cu₂S nanocrystals with abundant interfacial sites enable highly efficient electrochemical CO₂ reduction. Electrochemical investigation shows that Bi-Cu₂S demonstrated the highest faradic efficiency toward formate production with simultaneously largely reduced overpotential and high partial current density compared with the control samples (Bi NPs, Cu₂S NRs, and physically mixture of Bi NPs and Cu₂S NRs), providing convincing evidence of the important role played by the interfacial synergy in promoting electrocatalysis. Density functional theory calculations show that electron transfer from Bi to Cu₂S led to the preferential stabilization of formate-evolution intermediates compared with CO formation and hydrogen evolution, which is consistent with the experimental results. This work highlights a unique interfacial design and synthesis of *p*-block metal and transition metal chalcogenide heterostructures to refine active sites for advanced electrocatalysis.

ARTICLE

Heterostructured Bi-Cu₂S Nanocrystals for Efficient CO₂ Electroreduction to Formate

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Electrochemical CO₂ reduction reaction (ECO₂RR) driven by renewable electricity holds promise to store intermittent energy in chemical bonds while producing value-added chemicals and fuels sustainably. Unfortunately, it remains a grand challenge to simultaneously achieve high Faradaic efficiency (FE), low overpotential, and high current density of ECO₂RR. Herein, we report the synthesis of heterostructured Bi-Cu₂S nanocrystals *via* a one-pot solution-phase method. The epitaxial growth of Cu₂S on Bi leads to abundant interfacial sites and the resultant heterostructured Bi-Cu₂S nanocrystals enable highly efficient ECO₂RR with largely reduced overpotential (240 mV lower than Bi), near-unity FE (>98%) for formate production, and high partial current density (2.4- and 5.2-fold higher J_{HCOO^-} than Cu₂S and Bi at -1.0 V vs. reversible hydrogen electrode, RHE). Density functional theory (DFT) calculations show that the electron transfer from Bi to Cu₂S at the interface leads to the preferential stabilization of the formate-evolution intermediate (*OCHO).

Introduction

Electrochemical CO₂ reduction reaction (ECO₂RR) is considered a promising strategy to sustainably recycle CO₂ into the anthropogenic carbon cycle, paving the road to a clean-energy future.¹⁻¹⁰ Despite its promise, ECO₂RR usually suffers from: i) significant overpotential, leading to low energy efficiency; ii) broad product distribution in aqueous electrolytes resulting from the multi-proton/electron transfer steps, and iii) the competition with the hydrogen evolution reaction (HER) and, thus, limited selectivity.^{1, 11, 12}

Metal and metal-based catalysts have been commonly used for the ECO₂RR to CO, formate, and C₂₊ products.^{1, 3, 7, 13, 14} Among those catalysts, nanostructured *p*-block metals such as Pb, In, and Bi demonstrate high selectivity toward formate production due to their passivation of HER.^{11, 12, 15, 16} Bi becomes especially attractive because of its low cost and non-toxicity.¹⁷ However, monometallic Bi usually suffers from high overpotential (>800 mV) as well as a low current density (<10 mA cm⁻²).^{18, 19} This can be attributed to the relatively weak binding of ECO₂RR intermediates (*e.g.*, *OCHO, *COOH) on Bi surfaces. Thus, a more reductive potential is required to stabilize those intermediates to enable electron and proton transfer steps. Alloying Bi with other transition metals is a common approach to tune the stability of reaction

intermediate, as shown in the Bi-Sn,^{11, 20-22} Bi-Cu,²³⁻²⁵ and Bi-Mo²⁶ systems. Nevertheless, a trade-off among overpotentials, Faradaic efficiencies (FEs), and current densities is commonly observed due to adsorption-energy scaling relations of alloy surfaces that impose constraints on attainable catalytic performances.²⁷⁻²⁹ It is therefore imperative to develop design strategies of ECO₂RR catalysts that demonstrate simultaneous high current densities, low overpotentials, and high FEs. To achieve this goal, constructing interfacial sites that can selectively stabilize relevant ECO₂RR intermediates on Bi surfaces could be a viable solution to improve electrokinetics while maintaining the high FE toward formate. To design an efficient interfacial site with Bi for ECO₂RR, transition metal chalcogenides (TMCs), especially cuprasulfide (Cu₂S), is promising as it demonstrates stronger binding of ECO₂RR intermediates thus a lower overpotential and higher current density than Bi.^{30, 31} However, HER is inevitable in Cu₂S systems.

Herein, we report proof-of-concept experimental and theoretical design of interfacial sites with a selectivity-governing and HER-suppressing domain (Bi) in concomitant with an electrokinetic-promoting domain (Cu₂S) for efficient ECO₂RR to formate. We developed a one-pot solution-phase synthesis method for preparing a new class of heterostructured Bi-Cu₂S nanocrystals with a microphone-like morphology. In 0.1 M KHCO₃, the Bi-Cu₂S catalyst manifests a much higher current density, lower overpotential, and higher FE toward formate production than its single component (Bi, Cu₂S) counterparts for ECO₂RR. Compared with Bi nanoparticles (NPs), the ECO₂RR onset potential on Bi-Cu₂S is positively shifted by 240 mV. By controlling the synthesis conditions, *e.g.*, the reaction temperature, the amount of reducing agent, and degassing temperature, the optimal Bi-Cu₂S catalyst can achieve near-unity formate selectivity at -1.2 V (vs. reversible hydrogen

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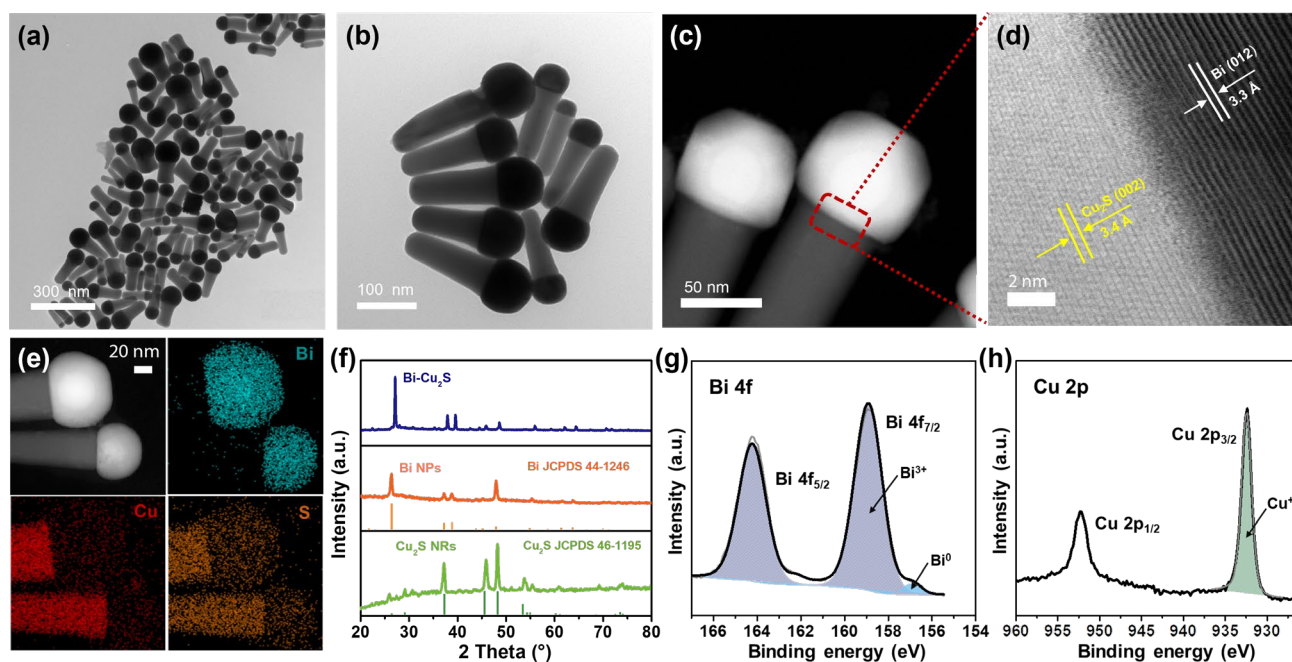


Figure 1. Structural characterizations of heterostructured Bi-Cu₂S nanocrystals. (a)–(b) TEM images; (c) STEM-HAADF image and (d) BF-STEM image of Bi-Cu₂S. (e) The STEM-HAADF image and the corresponding X-EDS mappings of Bi-Cu₂S. (f) XRD patterns of Bi NPs, Cu₂S NRs and Bi-Cu₂S. (g) Bi 4f XPS spectrum and (h) Cu 2p XPS spectrum of Bi-Cu₂S.

electrode, RHE) with a high current density of 18.2 mA cm⁻², outperforming many previously reported catalysts.^{32–34} Density functional theory (DFT) calculations showed that the interfacial site preferentially stabilizes the formate-evolution intermediate *OCHO compared with the *COOH intermediate toward CO formation and the *H intermediate toward H₂ generation. The stabilization of key intermediates was attributed to the electron transfer from Bi to Cu₂S moieties at the interface.

Results and Discussion

Heterostructured Bi-Cu₂S nanocrystals were synthesized *via* a one-pot wet chemical approach (see Supporting Information, SI). The TEM images of the as-synthesized Bi-Cu₂S (Figure 1a, 1b, Figure S1) show that the Bi ‘head’ with a size of 76 nm and the 103 nm Cu₂S ‘body’ is well-connected, forming a heterostructure interface. A clear interfacial boundary was observed in a bright-field (BF) STEM image (Figure 1d), suggesting the epitaxial growth between Cu₂S and Bi. From the STEM image, we can observe an interplanar distance of 3.3 Å in the Bi domain, corresponding to the (012) crystalline plane of rhombohedral Bi. The lattice spacing of Cu₂S is 3.4 Å, which can be attributed to the (002) plane of hexagonal Cu₂S. High-angle annular dark-field STEM (HAADF-STEM) (Figure 1c) x-ray energy dispersive spectrometry (X-EDS) mapping (Figure 1e) suggests the enrichment of Bi at the head while the signal of Cu and S distributes across the entire structure and enriches in the rod, confirming the formation of abundant Bi-Cu₂S interfacial sites. Figure 2a shows a schematic illustration of the nucleation and growth of heterostructured Bi-Cu₂S nanocrystals. The

transmission electron microscopy (TEM) images of Bi-Cu₂S along the time sequence after the injection of sulfur-containing surfactants suggest that the Bi nucleates first and serves as seeds for the deposition, nucleation, and growth of Cu₂S domains (Figure 2b). For comparison, Bi NPs and Cu₂S nanorods (NRs) were also synthesized according to reported methods (SI, Figure S2).^{12, 35} A typical rhombohedral crystal structure of Bi-Cu₂S and Bi and a hexagonal structure of Cu₂S in the x-ray diffraction (XRD) patterns were observed (Figure 1f), consistent with the lattice spacing obtained in Figure 1d. No obvious Cu₂S peak presents in the Bi-Cu₂S due to the overlapping of diffraction peaks between Bi and Cu₂S. The x-ray photoelectron spectroscopy (XPS) of Bi 4f spectrum for Bi-Cu₂S (Figure 1g) shows the peaks at 156.93 and 158.91 eV, which are attributed to Bi⁰ and Bi³⁺, respectively. Compared to the XPS result of pure Bi NPs (Figure S8b), Bi-Cu₂S has no peak shifted, suggesting the chemical composition and valence state of Bi-Cu₂S in the bulk keep unchanged. The Cu 2p XPS spectrum of Bi-Cu₂S (Figure 1h) shows a single Cu 2p_{3/2} feature at 932.3 eV, which can be assigned to Cu¹⁺ or Cu⁰. The deconvolution of the Cu LMM spectra (Figure S7) further distinguishes the existence of Cu¹⁺ from Cu⁰ in Bi-Cu₂S.

The as-synthesized Bi-Cu₂S and control samples of Bi NPs and Cu₂S NRs were deposited on activated carbon and surface-activated through a ligand-stripping method (SI, Figure S5). The catalyst ink was prepared and airbrushed onto a carbon paper (SI). The ECO₂RR testing was conducted in CO₂-saturated 0.1 M KHCO₃ in a gas-tight H-cell. Before the measurement, all the samples were further activated *via* potential cycling between -1.2 V and 0 V vs. RHE in Ar-saturated solution for 10 cycles at a

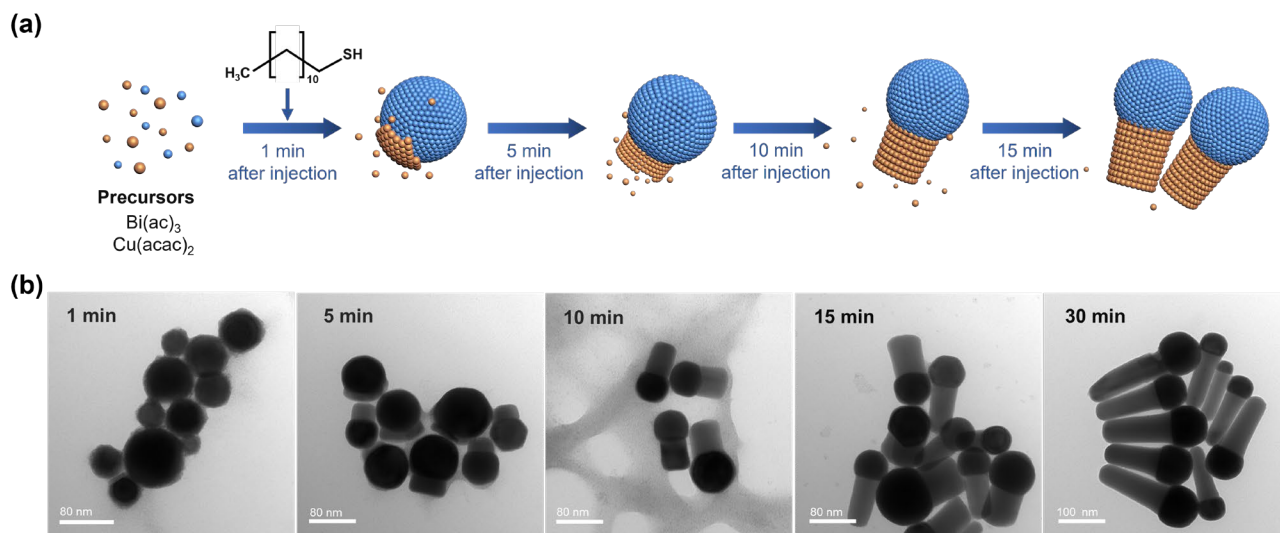


Figure 2. (a) Schematic illustration of the nucleation and growth of the heterostructured Bi-Cu₂S nanocrystals. (b) TEM images of Bi-Cu₂S at different time intervals after introducing 1-dodecanethiol at 220 °C.

scan rate of 20 mV s⁻¹. Cyclic voltammograms (CVs) were then recorded first in Ar and then in CO₂-saturated solutions (**Figure S10, S11, S12**). To further evaluate the catalytic performance of Bi-Cu₂S, linear sweep voltammetry (LSV) curves were performed. In **Figure 3a**, Bi-Cu₂S not only shows a higher current density than the two control samples (Bi NPs and Cu₂S NRs) in a wide range of potential from -0.8 V to -1.2 V vs. RHE, but also demonstrates 240 mV more positive onset potential than Bi. At -1.0 V vs. RHE, Bi-Cu₂S demonstrates a 4.9-fold increase of total current density compared with Bi. To probe the product distribution, the electrolysis measurements in a wide range of applied potentials (-0.8 to -1.2 V) were carried out. Gas chromatography (GC) was used to detect gas products, while ¹H nuclear magnetic resonance (NMR) spectrometer was employed to analyze liquid-phase products. The Bi-Cu₂S demonstrated the highest partial current density for formate production (J_{HCOO^-}) at all applied potentials compared with Bi NPs and Cu₂S NRs (**Figure 3b**). Meanwhile, the J_{HCOO^-} of Bi-Cu₂S rapidly increased from -0.9 V, exhibiting a striking difference from the control samples. The FE of formate production ($\text{FE}_{\text{HCOO}^-}$) on Bi-Cu₂S is shown in **Figure S10c**. Over 90% of $\text{FE}_{\text{HCOO}^-}$ was achieved at the applied potential of -1.0 V. Especially, near-unity HCOO⁻ selectivity was obtained at the potential of -1.2 V, exceeding most of the state-of-art catalysts for formate production.^{7, 19} **Figure 3e** shows the FEs over Bi-Cu₂S, Bi, and Cu₂S. The $\text{FE}_{\text{HCOO}^-}$ of the designed Bi-Cu₂S was higher than the two control samples at all applied potentials. Especially, the $\text{FE}_{\text{HCOO}^-}$ of Bi-Cu₂S was 92.4% at -1.0 V, which is ~1.4 times higher than the Cu₂S NRs (65% $\text{FE}_{\text{HCOO}^-}$). The production rate of formate on Bi-Cu₂S reached 131 μmol cm⁻² h⁻¹ at -1.0 V, which is 3.5 times higher than the Bi NPs (**Figure S16**). Furthermore, Bi-Cu₂S showed a much lower FE of H₂ (FE_{H_2}), indicating that Bi-Cu₂S preserved the HER-inhabiting property. To verify that the interfacial sites of Bi-Cu₂S play a key role in the ECO₂RR, Bi NPs

and Cu₂S NRs were physically mixed (Bi NPs+Cu₂S NRs) as a control sample (**Figure S3**). Compared with the physical mixture of Bi NPs and Cu₂S NRs (**Figure S13, S14**), Bi-Cu₂S showed a larger current density and higher $\text{FE}_{\text{HCOO}^-}$, indicating the importance of a well-connected interface on Bi-Cu₂S in optimizing the ECO₂RR kinetics. Moreover, we tested the ECO₂RR performance of Bi-Cu₂S heterostructures with 5-, 15-, 30-, and 120-minutes reaction time after injecting the sulfur-containing surfactant, denoted as Bi-Cu₂S/5, Bi-Cu₂S/15, Bi-Cu₂S/30 (which is the Bi-Cu₂S catalyst in this work), and Bi-Cu₂S/120. The TEM images (**Figure S4**) show that there are many impurities and unreacted precursors in the Bi-Cu₂S/5 and Bi-Cu₂S/15. The reaction is complete and there are no more impurities in the sample when the reaction time is more than 30 min. In **Figure S15**, Bi-Cu₂S under complete reaction conditions (Bi-Cu₂S/30 and Bi-Cu₂S/120) demonstrate more positive onset potentials than the incomplete ones (Bi-Cu₂S/5 and Bi-Cu₂S/15). Bi-Cu₂S/30 shows the highest partial current density (J_{HCOO^-}) and Faradic efficiency of formate ($\text{FE}_{\text{HCOO}^-}$) production at the potential from -0.9 to -1.2 V vs. RHE. Especially, Bi-Cu₂S/30 demonstrates a much higher J_{HCOO^-} and $\text{FE}_{\text{HCOO}^-}$ than the Bi-Cu₂S/5 and Bi-Cu₂S/15, indicating the negative impact of the incomplete reactants in the CO₂ reduction reaction. Furthermore, both J_{HCOO^-} and $\text{FE}_{\text{HCOO}^-}$ on Bi-Cu₂S/120 catalysts slightly decrease compared to Bi-Cu₂S/30. This can be attributed to the larger size and fewer active sites of Bi-Cu₂S/120. This result provides evidence that the interfacial synergy in Bi-Cu₂S plays an important role in promoting electrocatalysis. Taking cumulatively, Bi-Cu₂S/30 demonstrates an extremely high HCOO⁻ selectivity, improved current density, and a much lower overpotential due to the synergistic effect at the interfacial sites of Bi-Cu₂S. The durability test of Bi-Cu₂S (**Figure S10d**) showed that the current density and FE stay stable after 10 h electrolysis.

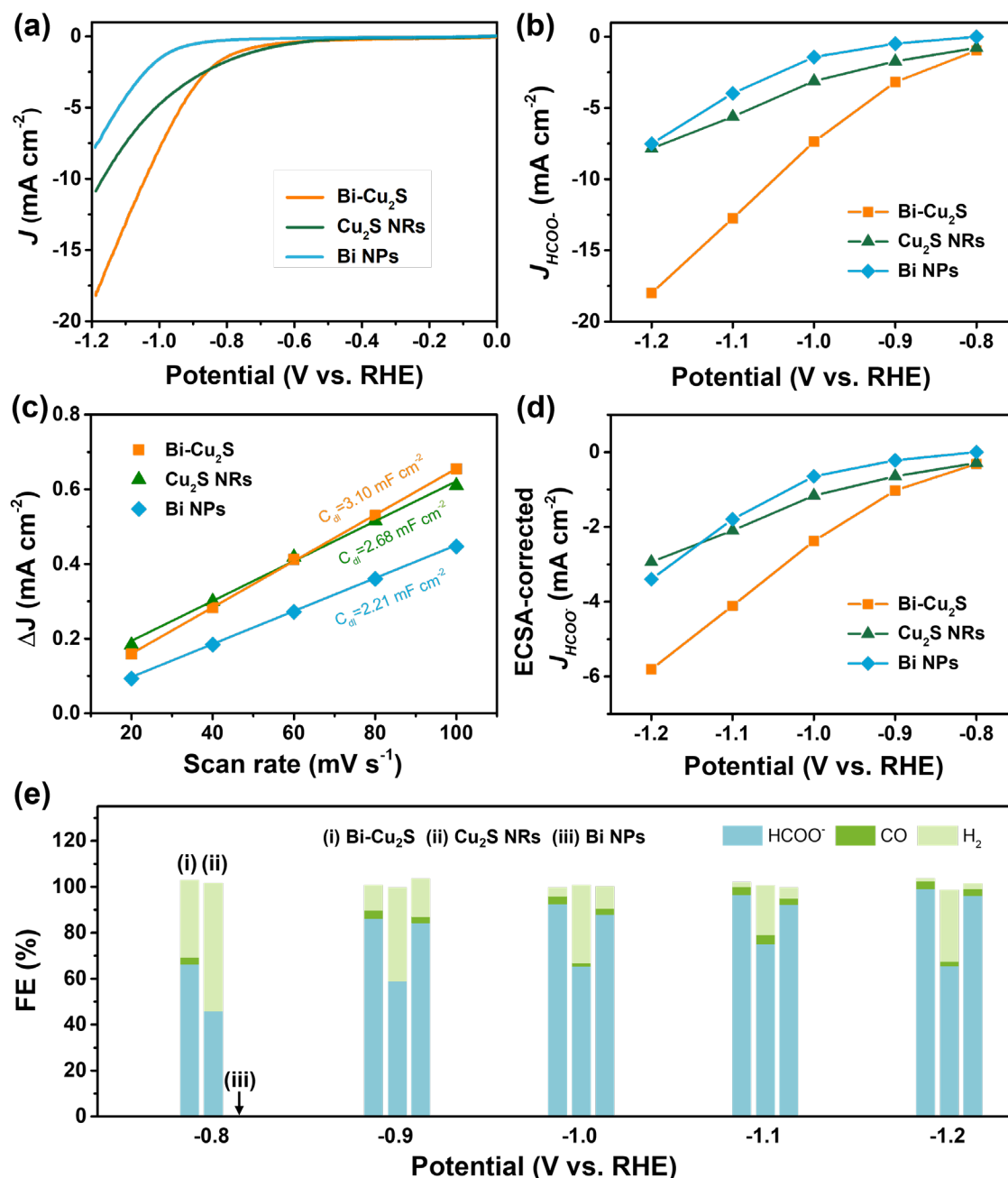


Figure 3. ECO₂RR on Bi-Cu₂S, Cu₂S NRs, and Bi NPs in the CO₂-saturated 0.1 M KHCO₃ electrolyte: **(a)** LSV curves; **(b)** Partial current density of formate at different potentials. **(c)** ECSAs of Bi-Cu₂S, Cu₂S NRs and Bi NPs. **(d)** ECSA-corrected current densities for formate. **(e)** Comparison of FEs for ECO₂RR on Bi-Cu₂S, Bi and Cu₂S electrodes at various applied potentials.

To gain insight into the origin of the ECO₂RR enhancement on Bi-Cu₂S, electrochemical surface area (ECSA) was measured by calculating double-layer capacitance (C_{dl}) to evaluate their ECSA-corrected current density (Figure S17, S18). The calculated values of C_{dl} (Figure 3c) for Bi-Cu₂S, Bi, and Cu₂S are 3.10, 2.21, and 2.68 mF cm⁻², respectively, indicating Bi-Cu₂S has more active sites than the controls. Meanwhile, the normalized ECSA current of formate (Figure 3d) shows that Bi-Cu₂S has higher intrinsic activity than Bi NPs and Cu₂S NRs at all applied potentials. The XPS was performed before and after the ECO₂RR

to gain a deeper insight into the valence state and surface composition of the Bi-Cu₂S catalyst (S1). In the Bi 4f XPS spectra of pure Bi NPs (Figure S8), only Bi³⁺ peak is observed, indicating Bi is surface-oxidized when re-exposure into the air after the CO₂ reduction. On the contrary, the XPS results of Bi-Cu₂S (Figure S6) reveal that Bi partially keeps the metallic state and the Bi⁰/Bi³⁺ ratio increases from 1:26 to 1:3 before and after the ECO₂RR. This observation suggests that the existence of Cu₂S stabilizes metallic Bi and suppresses its surface oxidation upon air exposure to promote ECO₂RR.¹²

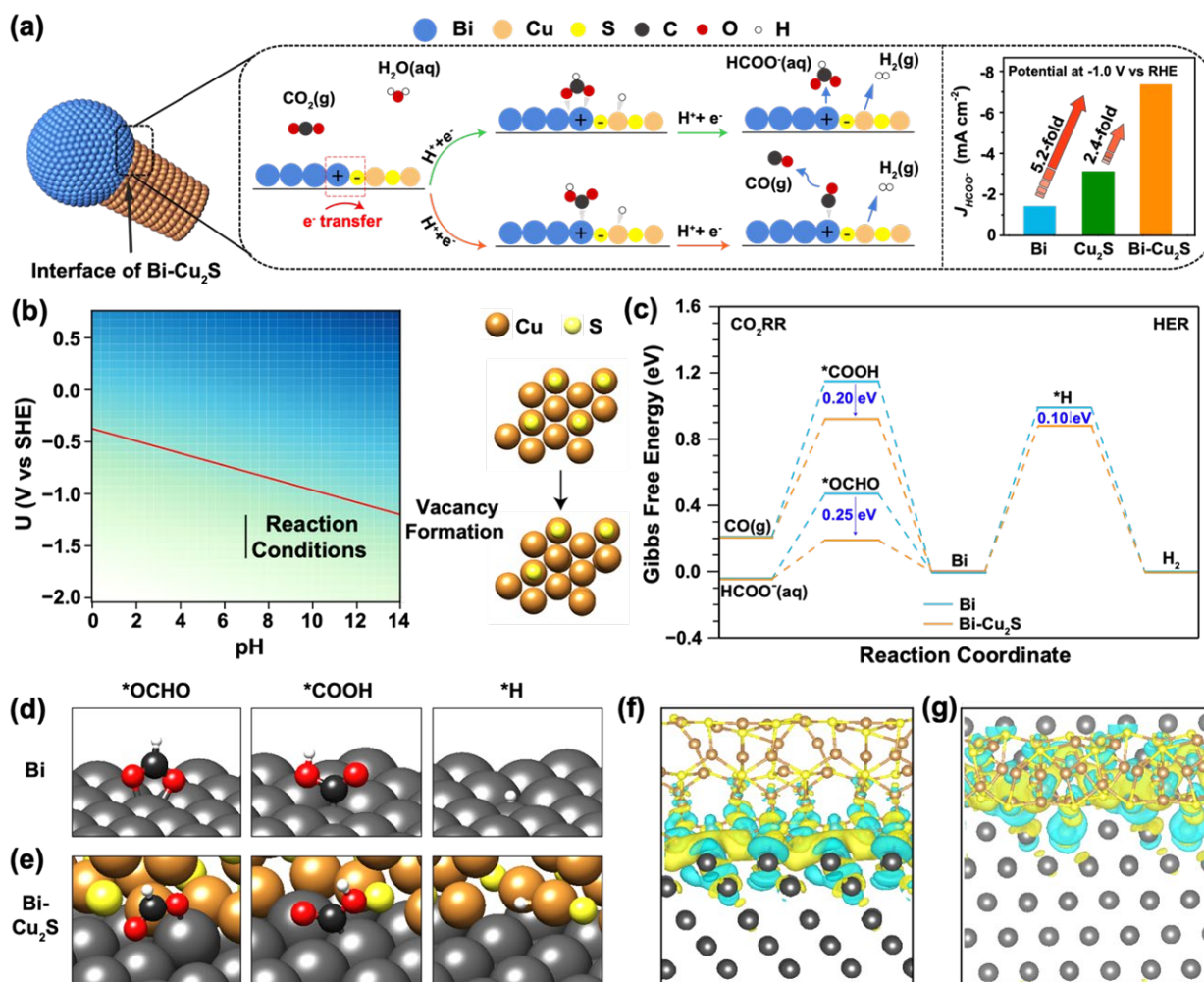


Figure 4. (a) Proposed CO₂ reduction mechanism on the Bi-Cu₂S interfacial system. (b) The sulfur vacancy formation pourbaix diagram. (c) Free energy diagrams of the ECO₂RR and HER on Bi (001) and Bi-Cu₂S model systems. Optimized geometry structures of key intermediates (*OCHO, *COOH, *H) on Bi (001) and Bi-Cu₂S systems are shown in (d) and (e), respectively. (Dark grey, brown, yellow, black, red, and white spheres denote Bi, Cu, S, C, O, and H atoms, respectively.) (f) and (g) are the top and front views of the charge density difference for Bi-Cu₂S interfacial surface, respectively. Cyan corresponds to an isosurface of $-0.001 \text{ e Bohr}^{-3}$ and yellow to $+0.001 \text{ e Bohr}^{-3}$.

To understand the interfacial synergy, DFT calculations were performed to investigate the energetics of key surface intermediates governing the kinetics of the ECO₂RR and the competing HER. Motivated by the X-EDS mapping of the synthesized Bi-Cu₂S showing the dispersed Cu₂S moieties on the Bi domain (Figure 1e), we built an interface model using a rhombohedral Bi (001) surface decorated with hexagonal Cu₂S NRs. Cu₂S NRs were constructed with the sulfur-terminated (001) orientation on all sides (Figure S19), which allows a stable interface to be formed between the two low-index surfaces. Under relevant ECO₂RR conditions, Cu₂S is partially reduced according to previous reports.³⁶⁻³⁸ The sulfur vacancy free formation energy of the stoichiometric Cu₂S (001) surface to generate H₂S(g) is -1.23 eV at potential -1.0 V vs. RHE (Figure S20 and Figure 4b, see SI for computational details). In Figure

4b, the sulfur vacancy free formation energy was plotted as a function of the operating potential U and pH. The red line is the potential U at which the vacancy starts forming. The vacancy free formation energy is negative below the red line indicating the feasibility of losing sulfur atoms on the surface. The reaction operating conditions were plotted as the black line, starting from -1.21 V to -1.61 V vs. SHE at pH=7, and at this condition, vacancies were formed on the surface. The generation of a second sulfur vacancy is energetically unfavorable, resulting in surface reconstruction. Thus, the interface model of Bi-Cu₂S contains one S vacancy in our model systems. This is consistent with our EDS spectra (Figure S9) that the ratio of S/Cu decreases after the electrolysis. Since ECO₂RR on Bi surfaces mainly produces formate and CO with two-electron transfers, we consider the first proton-coupled electron transfer with the

protonation of the C atom to form the *OCHO intermediate or O atom to form the *COOH intermediate.³⁹ The *OCHO and *COOH intermediates can be further reduced to HCOO⁻ and CO, respectively (**Figure 4a**). The HER *via* the *H intermediate is also considered at the interfacial sites. The reaction pathway and the optimized geometries for each intermediate are shown in **Figure 4c-e**, for both Bi and Bi-Cu₂S systems (**See Figure S21 for detailed geometries**). The formation of the *COOH intermediate is significantly uphill in free energy than the *OCHO intermediate on both surfaces, leading to a favorable production of HCOO⁻, consistent with the experimental results of a much higher FE_{HCOO⁻} than FE_{CO}. The Vomer step of the HER is highly unfavorable since the *H intermediate binds very weakly on Bi sites, resulting in a suppressed HER under CO₂ reduction conditions on Bi.^{18, 40}

While the ECO₂RR is facilitated in both Bi and Bi-Cu₂S systems, the extent of stabilization of the CO⁻ and HCOO⁻ evolution intermediates varies. Attributed to the interactions between Bi and Cu₂S, *OCHO and *COOH are stabilized by 0.25 eV and 0.20 eV on the Bi-Cu₂S interfacial site, respectively, leading to a reduced overpotential and improved selectivity toward formate production compared with that on pure Bi. The *H intermediate is merely stabilized by 0.10 eV due to its adsorption on the Cu site of Bi-Cu₂S. Therefore, the HER is still inhibited in Bi-Cu₂S, consistent with our experiment results in **Figure 3e**. We further analyzed the local electronic structure of the interface and the adsorbates to gain insights into the improved performance. **Figure S22-S23** shows the isosurfaces of the Cu₂S-induced charge density difference, and **Figure S24** shows the Bader charge analysis⁴¹, both of which show that Bi is electron-deficit, which is consistent with the fact that a Schottky interface between Bi and Cu₂S could lead to the electron flow from Cu₂S to Bi^{42, 43}. For a bare Bi-Cu₂S surface (**Figure 4f-g**), the Bi substrate is electron-deficit, especially for Bi atoms forming bonds with S atoms, which plays an important role in electrostatically stabilizing the *OCHO and *COOH intermediates since both are negatively charged as shown in **Figure S23** of adsorbate-induced charge density difference on Bi (001).

Conclusions

In summary, we have reported a one-pot synthesis of heterostructured Bi-Cu₂S nanocrystals for the ECO₂RR toward formate production. Detailed structural characterizations proved the successful construction of a well-connected, epitaxial interface between Bi and Cu₂S. Systematic electrochemical investigations demonstrated much enhanced ECO₂RR activity without the sacrifice of high selectivity at the interface between Bi and Cu₂S. Compared with Bi NPs, Cu₂S NRs, Bi+Cu₂S physical mixture, Bi-Cu₂S presented the highest FE at all applied potentials toward formate production, with partial current densities increased by 5.2-fold, 2.4-fold, 5.3-fold at -1.0 V vs. RHE, respectively. The onset potential of Bi-Cu₂S is 240 mV more positive than that of Bi NPs. These results provide clear evidence that the interfacial synergy in Bi-Cu₂S plays a pivotal

role in promoting electrocatalysis. DFT calculations suggest that the electron transfer from Bi to Cu₂S at the interface stabilized the ECO₂RR intermediates, particularly for *OCHO toward HCOO⁻ evolution compared with *COOH to CO and *H to H₂. This work highlights a unique design strategy of *p*-block metal and TMC heterostructures to fine tailor active sites for advanced electrocatalysis.

Author Contributions

X.H. and T.M. contributed equally to this work.

Conflicts of interest

There are no conflicts to declare.

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