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The bio-inspired heterogeneous single-cluster catalyst Ni100–Fe₄S₄ for enhanced electrochemical CO₂ reduction to CH₄†

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Electrochemical conversion of CO₂-to-CH₄ is a process of converting the inert greenhouse gas into energy molecules. It offers great promise for the transformation of carbon-neutral economy. However, achieving high CH₄ activity and selectivity remains a major challenge because the electrochemical reduction of CO₂-to-CH₄ is accompanied by various C₁ intermediates at the catalytic site, involving multiple proton-coupled electron transfer processes. Herein, different from the traditional designing strategy, we propose a bio-inspired theoretical design approach to construct a heterogeneous single-cluster catalyst Ni100–Fe₄S₄ at the atomic level, which may show high CO₂ electroreduction performance. Combined with the crystallographic data and theoretical calculations, Ni100–Fe₄S₄ and CO dehydrogenase exhibit highly similar catalytic geometric active centers and CO₂ binding modes. By exploring the origin of the catalytic activity of this biomimetic structure, we found that the activation of CO₂ on Ni100–Fe₄S₄ theoretically exceeds that on natural CO dehydrogenase. Density functional theory calculations reveal that the dehydrogenase enzyme-like Fe–Ni active site serves as an electron enrichment ‘electro-bridge’ (an electron-rich highly active catalytic site), which can activate CO₂ molecules efficiently and stabilize various intermediates in multistep elementary reactions to selectively produce CH₄ at a low overpotential (0.13 eV). The calculated CO₂ electroreduction pathways are well consistent with the nickel-based catalytic materials reported in experimental studies. Our work showcases and highlights the rational design of high-performance catalytic materials via the biomimetic methodology at the atomic level.

Received 29th November 2022,

Accepted 26th December 2022

DOI: 10.1039/d2nr06665c

rsc.li/nanoscale

1. Introduction

The global energy environmental crisis is particularly prominent in the 21st century. The excessive consumption of fossil fuels has not only brought about the energy crisis, but also caused global warming,¹ water pollution,² extreme climate change,³ and extinction of biological populations⁴ due to excessive CO₂ emissions. Developing a carbon-neutral strategy provides breakthrough solutions to the global crisis including energy, food, and climate change. Electrochemical CO₂ reduction (CO₂RR) to useful fuels and value-added chemical feedstocks offers promising pathways for carbon neutrality.

However, the rational design of low-cost, efficient, high-selectivity CO₂ electrocatalysts remains a great challenge.^{5,6} Currently, the two main strategies for the design of highly active CO₂RR electrocatalysts are to increase the number of active sites on a given electrode and increase the intrinsic activity of each active site.⁷ They may have transport problems and consume more expensive materials upon increasing the number of active sites on a given electrode.⁷ In addition, compared with the former strategy, the latter strategy improves from key origins of catalyst activity. However, significant challenges remain in increasing the intrinsic activity of each active site, which requires a dynamic understanding of the atomic structure of the catalyst at the electronic structure level.⁵ For example, Li *et al.* cleverly designed a metal–organic framework based bimetallic site catalyst with self-adaptive characteristics,⁸ which achieved selective CO₂ photoreduction to CH₄. Zhang *et al.* designed a carbon nanotube-based nickel phthalocyanine catalyst at the molecular level, achieving selective CO₂ reduction.⁹ Wang *et al.* designed a Ni–N–C complex catalyst from the electronic structure level by combining theoretical calculation and experiment, achieving efficient CO₂RR.¹⁰ The electronic structure of the catalyst surface can also be adjusted

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†Electronic supplementary information (ESI) available. See DOI: <https://doi.org/10.1039/d2nr06665c>

through surface modification, such as tailoring on the surface of copper-based catalysts for C–C coupling¹¹ and the etching strategy of metal–organic framework materials.¹² At the same time, the addition of artificial intelligence provides more ideas for catalyst design. Zhong and Tran *et al.* combined active machine learning with DFT calculations to develop a catalyst computational design framework.^{13,14} They further performed approximately 4000 DFT simulations, which combined with experimental testing finally revealed Cu–Al materials with highly efficient CO₂-selective reduction properties.¹⁴ Therefore, the current design of excellent CO₂RR catalysts is extremely challenging, requiring expensive high-throughput calculations, as well as a deep understanding of the microscopic geometry and electronic structure of materials.^{5,6} In other words, bionics has been gradually applied to the design of various catalysts in recent years.^{15–20} From the perspective of Shafaat *et al.*, it is highly successful to design efficient CO₂ reduction catalysts by combining biological and chemical strategies.¹⁵ It is fascinating and highly promising to propose a strategy for the bio-inspired design approach of CO₂RR catalysts at the atomic level.

The biological redox conversion of CO₂, N₂, O₂ and H₂ is an important process in biogeochemical cycles. Abundant evidence suggests that both the existence of the current biosphere and the origin of the earliest life on the Earth rely on the biological capacity to fix CO₂ and convert into living matter.^{21,22} To date, seven carbon fixation pathways in nature have been discovered. As the workhorses of large-scale CO₂ fixation in nature, the Calvin cycle²³ combined with photosynthesis was first recognized in 1948, followed by the reverse Krebs cycle²⁴ (reverse TCA cycle) in 1966, the reductive acetyl-CoA pathway²⁵ (Wood–Ljungdahl pathway) in 1972, the 3-hydroxypropionate bicycle²⁶ (3-HP/malyl-CoA cycle) in 1993, the dicarboxylate/4-hydroxybutyrate cycle²⁷ in 2007 (Di-4HB cycle), the 3-hydroxypropionate-4-hydroxybutyrate cycle²⁸ in 2008 (3HP-4HB cycle), and the enoyl-CoA carboxylases/reductases²⁹ in 2016. Among these CO₂ fixation pathways in nature, the acetyl-CoA (Wood–Ljungdahl pathway) pathway is the most ancient and relies on metalloenzymes containing transition metal active centers for CO₂ activation.³⁰ This kind of ancient metalloenzyme is named Carbon monoxide dehydrogenase/acetyl-CoA synthase (CODHase/ACS). It may be the earliest biological carbon-fixing enzyme evolved by natural thermophilic anaerobic microorganisms in the autotrophic theory of the origin of life,^{31–33} endowing it with the ability to live in the CO₂-rich atmosphere that existed during the Archean Eon.^{34,35}

CO dehydrogenase has been proven to exhibit very good biological activity in CO₂ reduction.^{15,36–38} Herein, inspired by the crystal structure of CO dehydrogenase II³⁹ isolated from *Carboxythermus hydrogenoformans* (CODHII_{Ch}), we designed a heterogeneous Fe₄S₄ single-cluster catalyst on the Ni (100) face (Ni100–Fe₄S₄) for the electrocatalytic reduction of CO₂. Compared with gaseous CO₂ and adsorbed CO₂ in CODHII_{Ch} from crystallographic analysis measured in experimental studies,^{39,40} the adsorbed CO₂ on Ni100–Fe₄S₄ exhibits longer bond lengths and smaller bond angles, which endows Ni100–Fe₄S₄ with better CO₂ activation. Furthermore, charge differ-

ence and density of states (DOS) analyses indicated that the electrons of Ni atoms and the Fe₄S₄ iron–sulfur cluster on the Ni (100) surface aggregated to the heterojunction interface, forming a highly active electron-rich Fe–Ni ‘electro-bridge’ catalytic site, which should be one of the key origins of efficient electrochemical reduction of CO₂-to-CH₄. The calculation results can well correlate with the nickel-based and FeS-based catalytic materials reported in the recent experiments.^{41–45} This bio-inspired design of the Ni100–Fe₄S₄ catalyst well combines the biological advantages of natural enzymes with the concepts of modern catalytic science, opening an avenue for the rational development of efficient artificial carbon fixation catalysts.

2. Computational details

All spin-polarized DFT calculations for periodic material systems were performed with the Vienna *Ab initio* simulation package (VASP)^{46,47} using the projector-augmented wave (PAW) method.⁴⁸ The exchange–correlation function was handled using the generalized gradient approximation (GGA) formulated by the Revised Perdew–Burke–Ernzerhof (RPBE).⁴⁹ The van der Waals (vdW) interactions are described using the DFT-D3 method in Grimme’s scheme.^{50,51} The interaction between the atomic core and electrons was described by the projector augmented wave method. The plane-wave basis set energy cutoff was set to 500 eV. The Brillouin zone was sampled with a 2 × 3 × 1 grid centered at the gamma (Γ) point for geometry relaxation. The perfect Ni bulk was fully optimized using 16 × 16 × 16 *k*-point Gamma (Γ) centered Monkhorst–Pack mesh sampling. The Ni (100) facets were modeled using a four-layer 4 × 3 slab containing 96 atoms with 13.91 Å × 10.43 Å in *x* and *y* directions, respectively, and a 15 Å vacuum region, ensuring the negligible lateral interaction of the adsorbates. The Fe₄S₄ cluster absorbs on the Ni (100) surface, with 13.91 Å × 10.43 Å × 20.22 Å simulation boxes containing 107 atoms, the bottom two layers were kept frozen at the lattice position. All structural models with a dynamic magnetic moment were fully relaxed to optimize without any restrictions until their total energy gradient converged to <1 × 10^{−5} eV, and the average residual forces were <0.02 eV Å^{−1}. Moreover, the Gibbs free energy calculation is performed with the computational hydrogen electrode (CHE) model,⁵² and the solvent effect is considered with the implicit solvent model implemented in VASPsol.^{53,54} Position-specific charge values are obtained using Bader analysis.

3. Results and discussion

3.1 Designing catalysts by learning from nature

Nature provides a blueprint to efficiently activate CO₂ molecules and selectively generate useful fuels and value-added chemical feedstocks using metalloenzymes. To accelerate high-performance CO₂RR catalyst discovery, we propose a

method for the rational design of catalysts assisted by ‘nature blueprints’. In this study, a dehydrogenase separated from *Carboxythermus hydrogenoformans* (a bacterium isolated from a Russian hot spring⁵⁵) was used as a ‘nature blueprint’ to aid in the structural design of Ni100–Fe₄S₄ (Fig. 1). CO dehydrogenases (CODHases) are the biological catalysts for the reversible oxidation of CO₂ to CO:³⁹

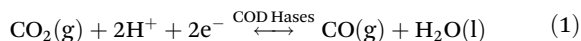


Fig. 1a shows the crystal structure of CO dehydrogenase II, which contains a special asymmetric [Ni–4Fe–5S] cluster. In the detailed crystal structure experimental data,^{39,56} the structure of CODHII_{Ch} with CO₂ reveals a triatomic ligand bridging Fe and Ni (Fig. 1b and c). This Fe–Ni bimetallic factor often plays a synergistic role in the catalytic reaction,^{8,57} which is beneficial for the activation and catalytic conversion of CO₂. Based on this special asymmetric [Ni–4Fe–5S] cluster enzymatic active center, we designed a heterogeneous catalyst by loading Fe₄S₄ single-clusters on the Ni surface. The calculation results show that the adsorption energies (the equation is given in ESI S1†) of the Fe₄S₄ cluster on the three most common surfaces of nickel^{58–62} Ni (100), Ni (111) and Ni (110) are –8.05 eV, –7.02 eV and –5.72

eV, respectively (Fig. S1†), indicating that the Fe₄S₄ cluster tends to adsorb on Ni (100) to form the most stable supported catalysts Ni100–Fe₄S₄. In addition, the Fe–O bonds (2.04 Å) and Ni–C bonds (1.99 Å) formed after the Ni100–Fe₄S₄ catalyst adsorbs CO₂ are only 0.01 Å and 0.03 Å different from those experimentally measured in CODHII_{Ch} (Fe–O 2.05 Å, Ni–C 1.96 Å), respectively (Fig. 1c and d). The similar adsorption bond length means that Ni100–Fe₄S₄ and CODHII_{Ch} have the same CO₂ binding mode, indicating that the Ni100–Fe₄S₄ catalyst may have enzyme-like catalytic activity.

3.2 Activating CO₂ beyond nature

The electroreduction of carbon dioxide by the catalyst is preferentially determined by the ability and degree of CO₂ activation. To activate CO₂ molecules, the active site basically needs to have the ability to adsorb CO₂. Since gaseous CO₂ molecules exhibit a linear shape and have stable triple-center π bonds (Fig. 2), ordinary physical adsorption hardly changes their geometric and electronic structures. Therefore, the activation of CO₂ molecules requires stronger chemisorption, and most forms of chemisorption will change the bond length and bond angle of CO₂ molecules, resulting in the splitting of its three-

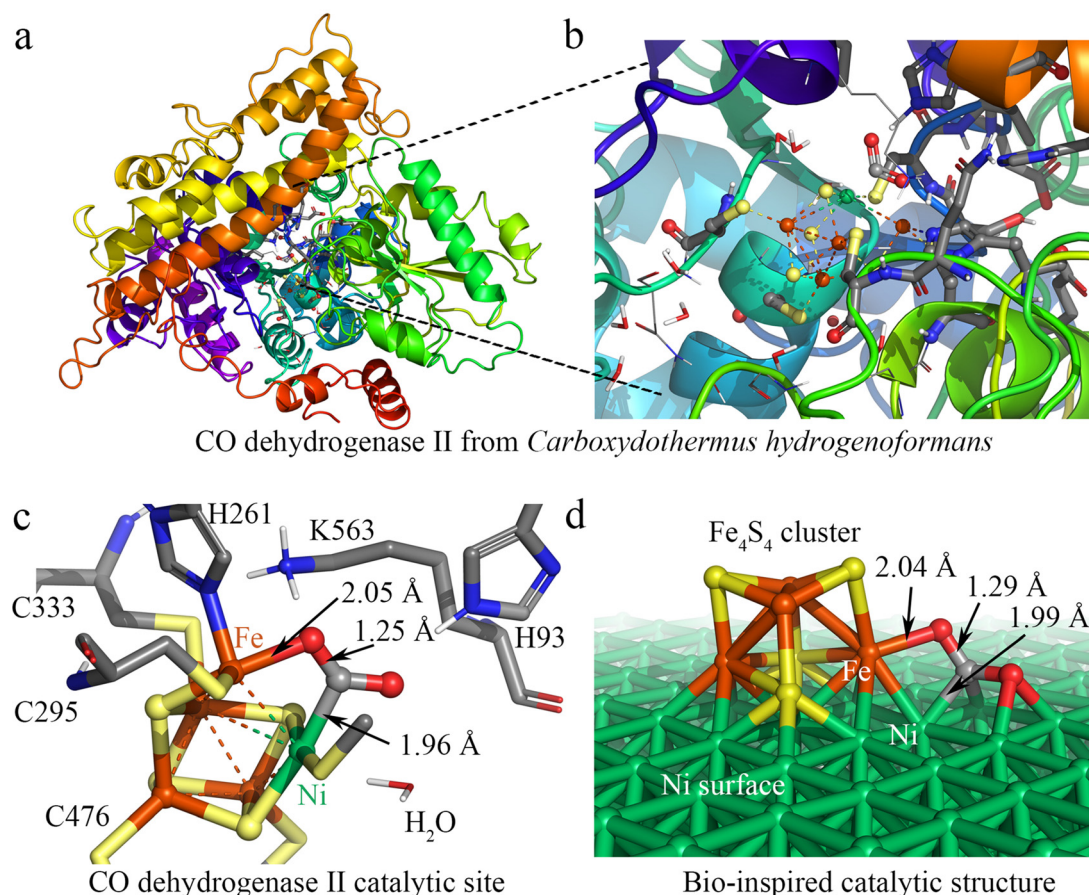


Fig. 1 Design of the Ni100–Fe₄S₄ catalyst inspired by CO dehydrogenase II. (a) The crystal structure of CODHII_{Ch}. (b) The catalytic center of CODHII_{Ch}. (c) The structure of the CODHII_{Ch} catalytic center combined with CO₂. (d) The structure of the bio-inspired heterogeneous Ni100–Fe₄S₄ catalyst. (In atomic coloring, white is H, gray is C, blue is N, red is O, yellow is S, orange is Fe, and green is Ni).

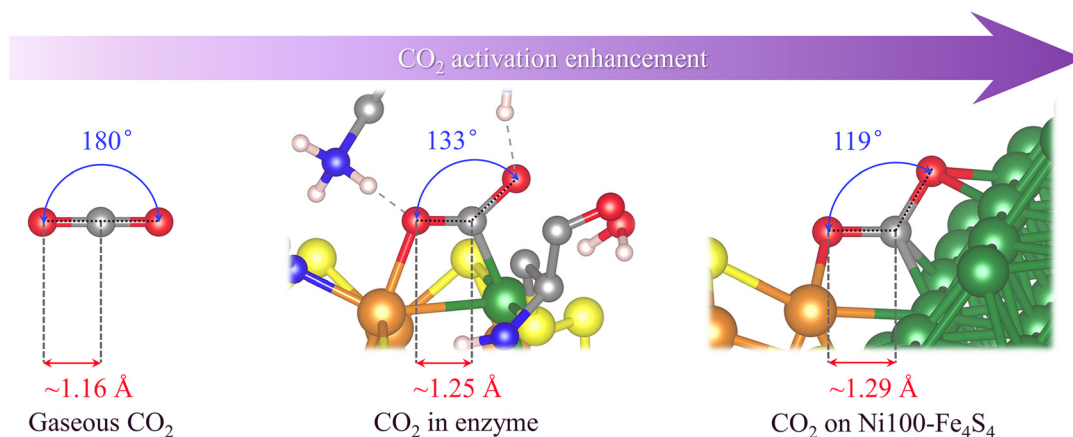


Fig. 2 Schematic diagram of the geometric structure of CO₂ in different adsorption states and CO₂ activation enhancement. (In atomic coloring, white is H, gray is C, blue is N, red is O, yellow is S, orange is Fe, and green is Ni).

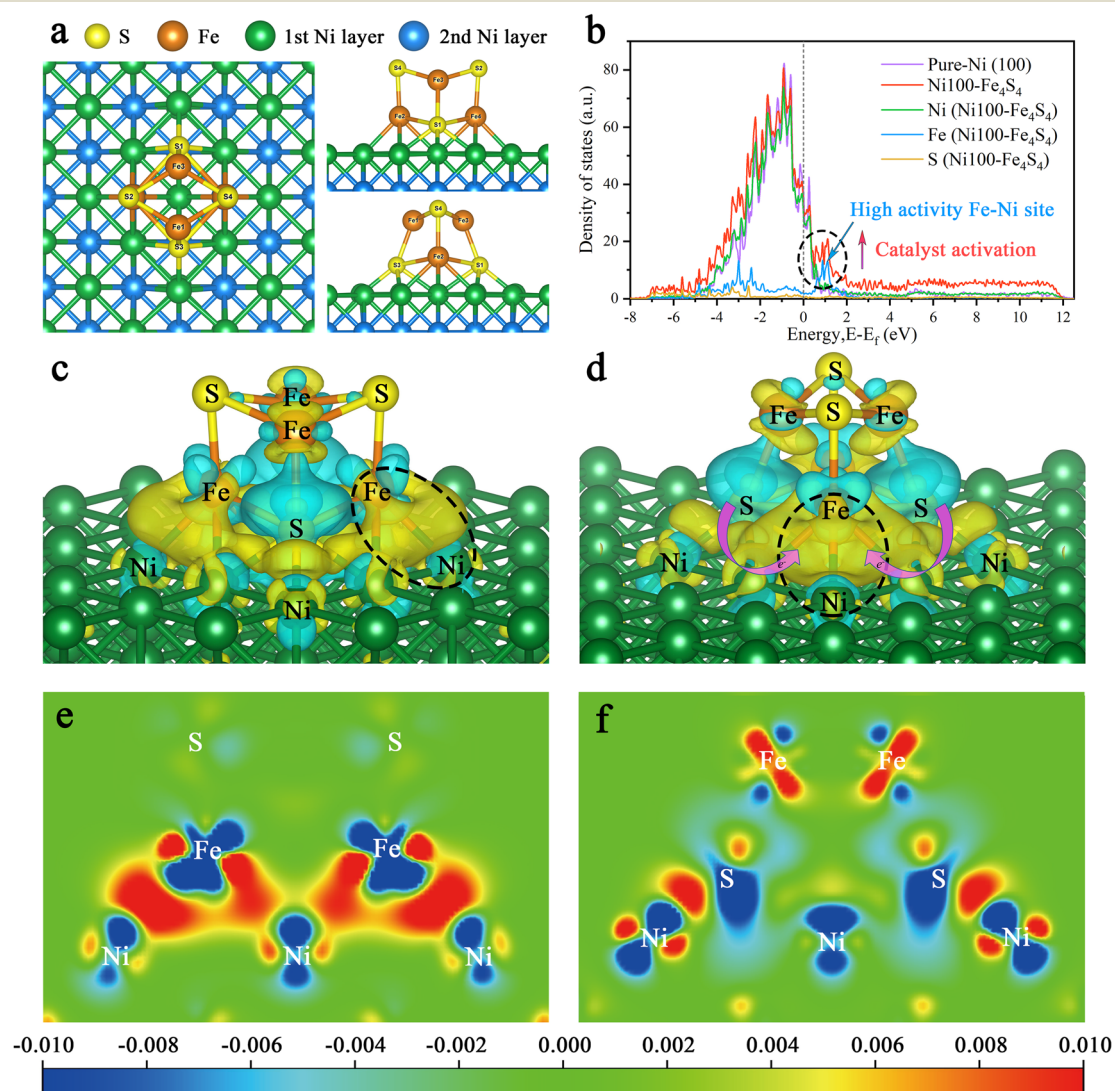


Fig. 3 The geometric and electronic structures of Ni100–Fe₄S₄. (a) The geometric structure of Ni100–Fe₄S₄. (b) The projected density of states (PDOS) onto the p and d states of Ni100–Fe₄S₄. (c and d) The charge difference analysis of the Ni100–Fe₄S₄ catalyst. (Light blue and yellow stand for the outflow and inflow of electrons, respectively. The black dotted circle represents the Fe–Ni site ‘electro-bridge’. Magenta arrows represent electron flow from S to Fe–Ni sites.) (e and f) The tangent plane of charge difference in the Ni100–Fe₄S₄ catalyst. (Blue stands for the outflow and red for the inflow of electrons.).

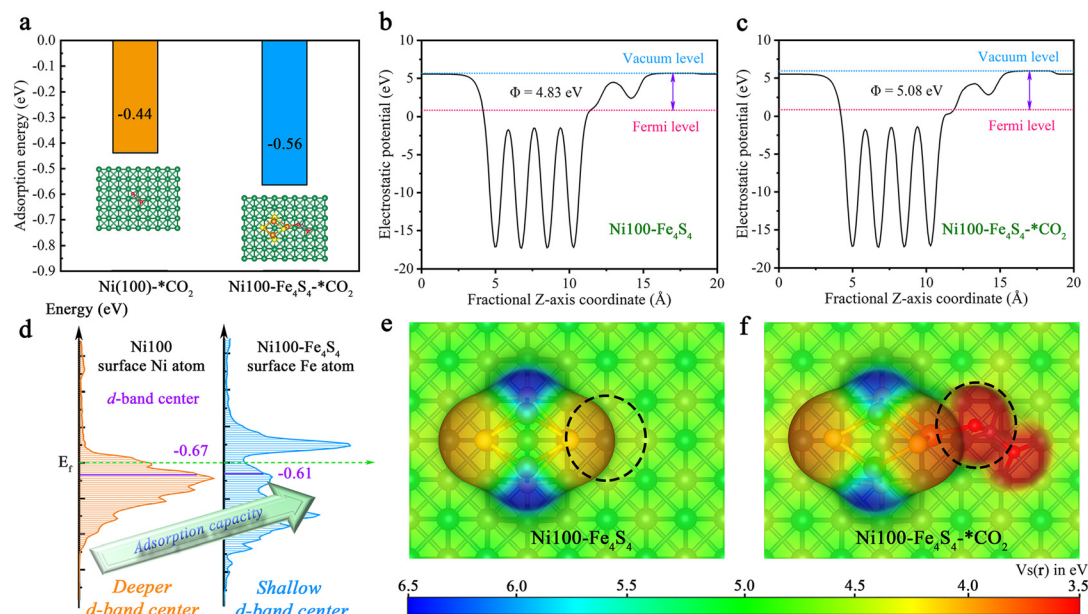


Fig. 4 The adsorption energy, d-band center, surface electrostatic potential and work function analysis of CO₂ adsorption. (a) Comparison of the adsorption energies between Ni (100) and Ni100–Fe₄S₄. (b) The work function of Ni100–Fe₄S₄. (c) The work function of Ni100–Fe₄S₄*CO₂. (d) Comparison of the d-band centers between the Ni atom on Ni (100) and the Fe atom on Ni100–Fe₄S₄. (e) Electron-density isosurface of Ni100–Fe₄S₄. (f) Electron-density isosurface of Ni100–Fe₄S₄*CO₂. The color bar stands for the scale of the electrostatic potential and the isosurfaces are plotted at the 0.002 e bohr⁻³ level.

center π bond. The geometric and electronic structures are subsequently changed, exhibiting a metastable activated CO₂ molecule.

As shown in Fig. 2, the crystal structure obtained by rotating anode X-ray diffraction³⁹ shows that the CO₂ molecules adsorbed on the catalytically active site of CODHII_{Ch} are no longer linear in gaseous CO₂. Its $\angle\text{O-C-O}$ angle is 133°, and the C–O bond length elongates from 1.16 Å to 1.25 Å compared with gaseous CO₂ molecules. Interestingly, in the structure of Ni100–Fe₄S₄ adsorbing CO₂, its $\angle\text{O-C-O}$ angle is smaller than that in CODHII_{Ch}, only 119°, and the C–O bond is also longer, reaching 1.29 Å. A smaller $\angle\text{O-C-O}$ angle and longer C–O bonds indicate that the designed Ni100–Fe₄S₄, inspired by the active center structure of CODHII_{Ch}, exhibits stronger CO₂ activation ability.

3.3 Fe–Ni ‘electro-bridge’ enhanced CO₂ activation

Bio-inspired strategies to control the performance of CO₂ activation focus on the geometric and electronic structures of the active site. We applied this methodology to the design of Ni100–Fe₄S₄. Fig. 3a shows the top view, front view and side view of the Ni100–Fe₄S₄ catalyst structure, which was obtained by loading Fe₄S₄ iron–sulfur clusters onto the Ni (100) surface. The geometric structure is the global energy minimum obtained by spin-polarized first-principles calculations. These iron–sulfur clusters, which are commonly used in biology to transfer electrons, are stabilized on the Ni (100) surface to form a special Ni100–Fe₄S₄ cluster heterojunction interface structure.

To unveil the origin of the structural activity of the Ni100–Fe₄S₄ heterojunction, we further calculated the projected density of states (PDOS) onto the p and d states of Ni100–Fe₄S₄ (Fig. 3b). In the PDOS of Ni100–Fe₄S₄, the peak near the Fermi level is mainly composed of Fe and Ni, implying that Fe–Ni is a highly active site. The Fe–Ni site in Ni100–Fe₄S₄ mimics the Fe–Ni catalytic sites in CODHII_{Ch}, which are crucial for CO₂ activation and reaction selectivity. Owing to the interaction of the heterojunction interface between Ni (100) and Fe₄S₄, the surface Ni atoms and Fe₄S₄ iron–sulfur clusters could transfer charge to the Fe–Ni site and an optimized polarization field is generated on its surface.

Furthermore, charge difference analysis results show that a large number of electrons are transferred from the Fe₄S₄ iron–sulfur clusters and the Ni (100) surface to the Fe–Ni site, forming a highly active electron-rich Fe–Ni ‘electro-bridge’ catalytic site on the heterojunction interface (Fig. 3c–f). Here, the role of S atoms is also very important. Through the charge difference calculation, we can observe that most of the charges on the Fe–Ni site come from S (Fig. 3d, magenta arrow), and the S atom acts as the charge supplier of the active site of the catalyst. Therefore, the Fe–Ni site can inject enough electrons into the CO₂ 2 π^* antibonding orbitals, disrupting the strong sp-hybridization symmetry of the carbon atom.

3.4 The mechanism of CO₂ adsorption and activation

Based on the above designed structure by bio-inspired strategies, the adsorption models for theoretical calculations can be constructed to gain insights into the CO₂ adsorption step

on Ni100-Fe₄S₄ from an atomic/electronic-level standpoint. Specifically, the thermodynamic energy conversion, d-band center, work function and electron-density isosurfaces were used to theoretically and systematically reveal the mechanism of the CO₂ adsorption step on Ni100-Fe₄S₄. To shed light on the characteristics and performance of Ni100-Fe₄S₄ adsorption of CO₂, we first analyzed the adsorption energy (the equation is ESI S2†). As depicted in Fig. 4a, Ni100-Fe₄S₄ shows a much more significant thermodynamic energy conversion of the CO₂ adsorption step (−0.56 eV) than pure Ni (100) (−0.44 eV). Pure Ni (100) has been widely proven to be a good CO₂ adsorbent both theoretically and experimentally.^{41,63–65} This means Ni100-Fe₄S₄ tends to well adsorb CO₂ in theory, which is well in line with the d-band center (Fig. 4d, the equation is ESI S3†). The favorable adsorption of CO₂ on Ni100-Fe₄S₄

will accelerate its CO₂RR processes and promote its CO₂RR activity.

To investigate the electronic structure and surface adsorption behavior on Ni100-Fe₄S₄, we calculated the electron-density isosurface (Fig. 4b and c) and the electronic work function (Fig. 4e and f) for Ni100-Fe₄S₄ and Ni100-Fe₄S₄-*CO₂, respectively. The work function is an essential physical property of metallic materials,⁶⁶ which has been widely used in the design and evaluation of various photo/electrocatalysts,^{67–69} can be obtained by calculating the difference between the electrostatic potential at the vacuum level E_{vac} and the electrostatic potential at the Fermi level E_{F} using ESI eqn (S4) and (S5).† The detailed electrostatic potential and work function calculation formula are given in ESI S3 and S4.† As shown in Fig. 4b and c, the work function of Ni100-Fe₄S₄ increases from

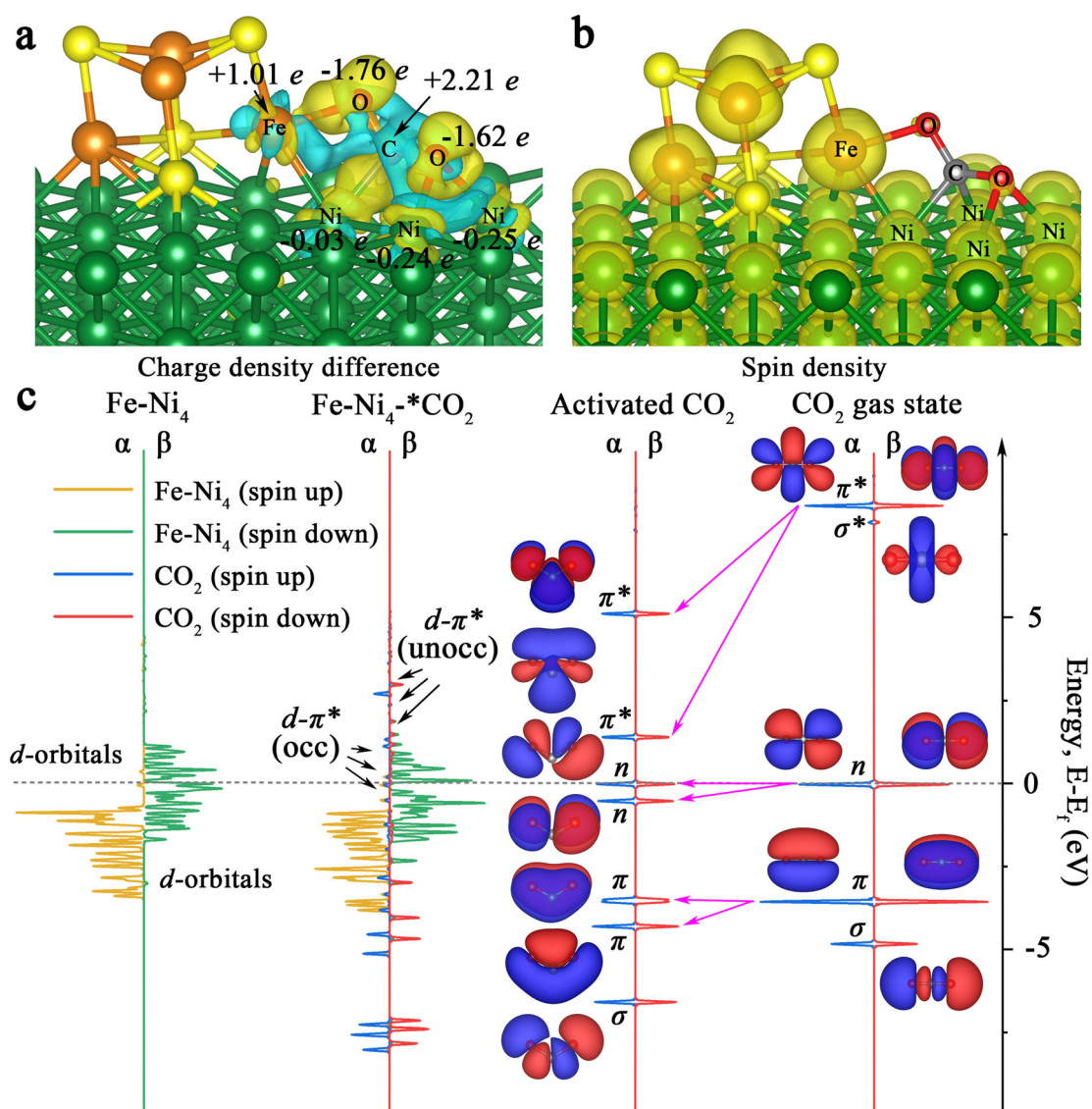


Fig. 5 Associative and activation mechanism analysis. (a) Charge density difference of CO₂ adsorption on Ni100-Fe₄S₄ (Light blue stands for the outflow and yellow for the inflow of electrons.). (b) Spin density of Ni100-Fe₄S₄ (Yellow stands for spin electrons.). (c) Projected electronic densities of states (PDOS) of FeNi₄, CO₂ and their interactive configuration FeNi₄-*CO₂.

surface are favorable for the nucleophilic attack on the electrophilic carbonyl carbon of CO₂ molecules. In addition, the electrostatic potentials around the isosurface of the O atom of CO₂ are at a low level (Fig. 4f, black dotted circle area), indicating a selective hydrogenation site.

Also, we calculated the charge distribution of Ni100-Fe₄S₄-*CO₂. As presented in Fig. 5a, we can clearly observe the electron inflow into the two O atoms of the adsorbed CO₂ in Ni100-Fe₄S₄-*CO₂ by the charge density difference. Further Bader charge analysis showed that electrons flowed mainly

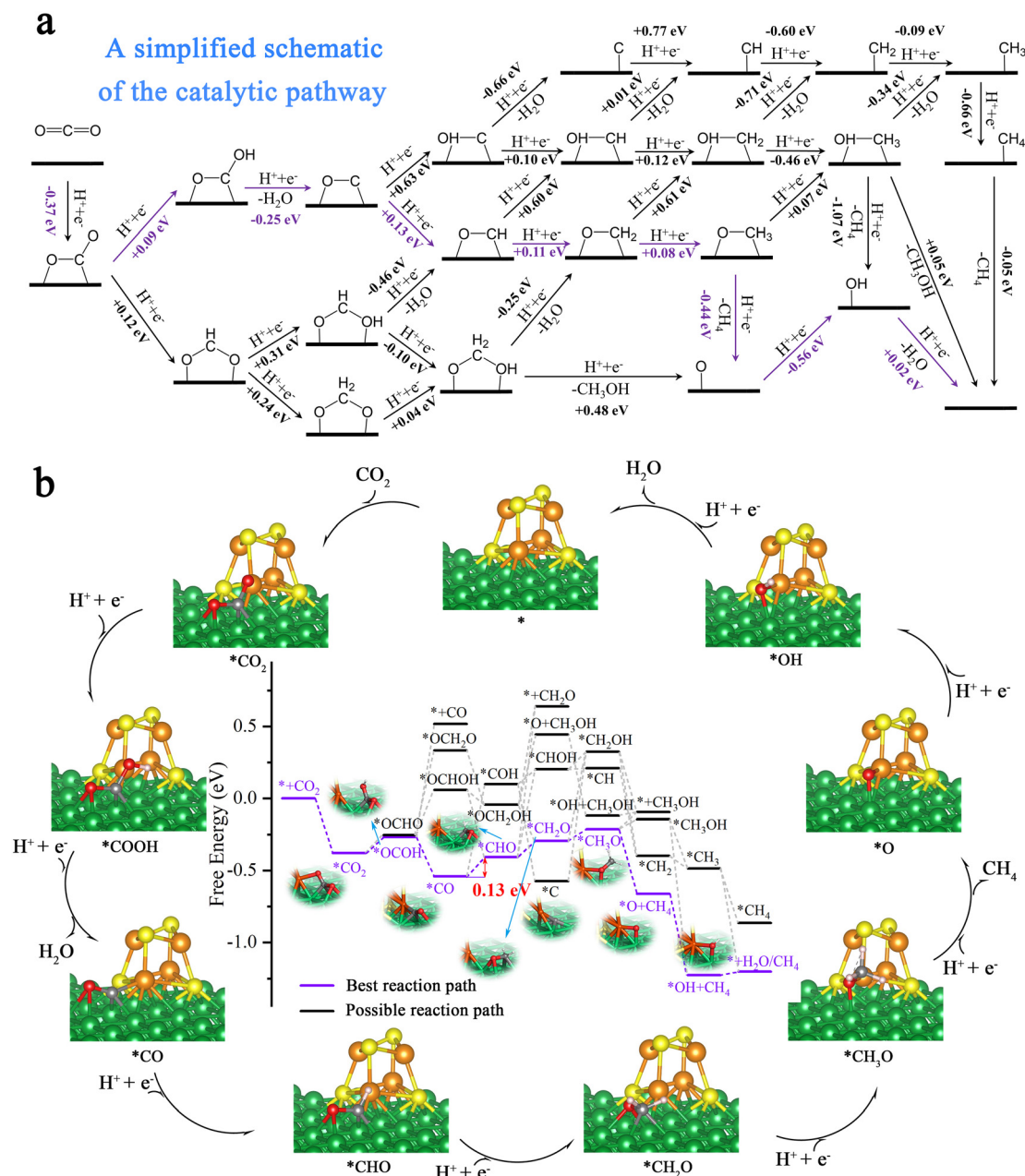


Fig. 6 The CO₂RR pathways on Ni₁₀₀-Fe₄S₄. (a) A simplified schematic of the free energy changes (ΔG) in the entire possible CO₂RR pathways; the energy optimal route is marked in purple. (b) The schematic diagram of the reaction mechanism of CO₂ electroreduction to CH₄ during the entire CO₂ reduction catalytic cycles.

from Fe atoms to CO₂ molecules attributed to the large spin polarization on Fe (Fig. 5b), which is consistent with the electron-density isosurface and work function analysis. Remarkably, in this charge transfer mode, the C atom of the CO₂ molecule has a highly positive charge (+2.21e), and the oxygen atoms have highly negative charges (−1.76e and −1.62e), which means that the most negatively charged oxygen atomic site (−1.76e) is more favorable for the subsequent electrocatalytic step to combine with H⁺. This selectivity of the hydrogenation site is consistent with subsequent Gibbs free energy calculations (Fig. 6, ESI Tables S1 and S4†).

To elucidate the bonding nature of the CO₂ molecules and Ni100–Fe₄S₄ involved in the associative mechanism, we further calculated the densities of states (DOS) of Ni100–Fe₄S₄–*CO₂ and Fe–Ni₄ sites (five atoms in Ni100–Fe₄S₄ directly affected by CO₂ molecules) for comparison (Fig. 5c). By comparing the DOS and molecular orbitals of the gaseous linear CO₂ molecule and the activated bent CO₂ molecule, we found that the π , n and π^* orbitals of the CO₂ molecule were split after activation. The π^* orbital splits into two empty orbitals with unequal energy levels in the activated CO₂ molecule, which matched well with the Fe–Ni₄ polarized β -spin d orbitals near the Fermi level, forming partially occupied d– π^* hybrid orbitals. Although the energy levels of the majority α -spin d orbitals of Fe–Ni₄ are about 2.0 eV lower than the π^* orbitals of activated CO₂, the results show that the interaction between the α orbitals and the π^* orbitals is obvious. This α -orbital interaction is due to the fact that there are still minority α orbitals present near the Fermi level, matching the π^* orbitals of

the CO₂ molecule. This CO₂ activation mechanism reveals that the electrons from the d orbitals of Ni100–Fe₄S₄ partially transfer to the empty π^* orbitals of adsorbed CO₂, which is consistent with the charge density difference analysis (Fig. 5a) and DOS analysis (Fig. 5c).

3.5 Reaction mechanism of CO₂ electroreduction to CH₄

In order to further evaluate the activity and selectivity of Ni100–Fe₄S₄ to convert CO₂* to hydrocarbon species, we studied the free energy changes (ΔG) of the entire CO₂ reduction catalytic cycles. We first considered the adsorption pattern of CO₂ molecules on the Ni100–Fe₄S₄ surface (ESI Fig. S2, Table S4†), DFT calculations showed that CO₂ molecules tended to be in the C–O site adsorption pattern (ESI Fig. S2c†) rather than the O–O site (ESI Fig. S2a†) adsorption pattern. This adsorption pattern is consistent with previously reported Ni-based materials.^{63,64} Then, the free energy calculation results (Fig. 6a) confirmed that the first hydrogenation step of the CO₂RR is preferentially on O to form COOH* rather than C (OCHO*) due to the low level of electrostatic potentials around the isosurface of the O atom of CO₂ (Fig. 4f, black dotted circle area, ESI Table S4†). During the entire hydrogenation steps and reduction mechanism of CO₂, the CO₂RR on Ni100–Fe₄S₄ follows the circulation pathway of * → CO₂* → COOH* → CO* → CHO* → CH₂O* → CH₃O* → O* → OH* → H₂O* → *, with the final products of CH₄ and H₂O (Fig. 6b). With this Ni100–Fe₄S₄ catalyst, the potential determining step (PDS) is CO* → CHO*, and the entire catalytic cycle has a limiting potential of only 0.13 eV, which is much lower than those

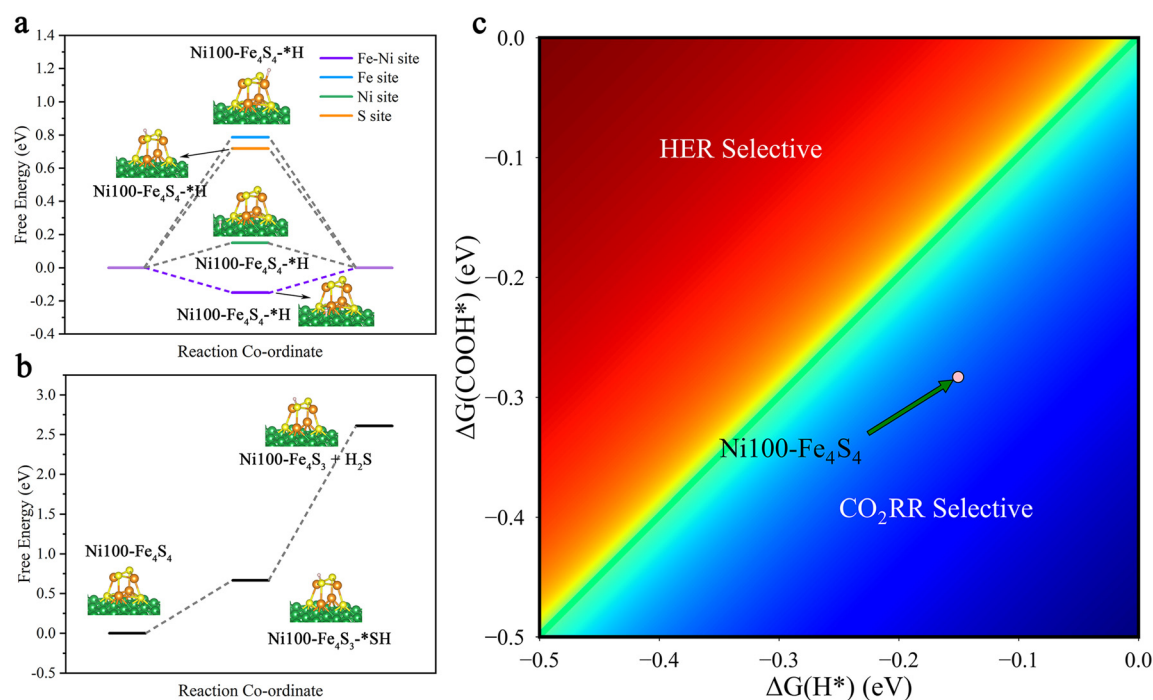


Fig. 7 Selectivity between the CO₂RR, the HER and the H₂SER. (a) Free energy diagrams of the possible HER mechanisms on the Fe–Ni, Fe, Ni and S sites. (b) Free energy diagrams of the possible H₂SER mechanisms on the cluster. (c) Selectivity for the CO₂RR vs. HER; the light pink data points represent the Ni100–Fe₄S₄ catalyst, and the blue region represents higher selectivity to the CO₂RR, while the red region to the HER.

of most reported CO₂RR catalysts in recent years (ESI Table S2†). Therefore, Ni100–Fe₄S₄ is potentially an efficient CO₂RR catalyst producing CH₄ at a low overpotential selectively.

3.6 Selectivity for CO₂ electroreduction

In order to study the stability of the cluster and the selectivity of the catalyst, we considered side reactions involving the hydrogen evolution reaction (HER) and the H₂S evolution reaction (H₂SER). The HER is an important competing side reaction, which can constantly consume proton–electron pairs from the electrolyte solution, restraining the faradaic efficiency of the CO₂RR significantly.^{14,71,72} To identify possible HER side-reaction sites, we first calculated Gibbs free energy changes (ΔG) of the HER ($* + H^+ + e^- \rightarrow H^*$) on the Fe–Ni, Fe, Ni and S sites (Fig. 7a, ESI Table S4†). According to the Brønsted–Evans–Polanyi relation,^{73,74} the result shows that the Fe–Ni site with a lower $\Delta G = -0.15$ eV is kinetically more favored due to the smaller reaction barriers. Besides, the calculated results show that hydrogenation is preferentially on O to form COOH* rather than C (OCHO*) both thermodynamically and kinetically (ESI Table S4,† Fig. 4). So, we compare the HER with the first hydrogenation step of the CO₂RR ($* + CO_2(g) + H^+ + e^- \rightarrow COOH^*$). The heatmap diagram of the Gibbs free energy changes (Fig. 7c) indicates that Ni100–Fe₄S₄ has higher selectivity toward the CO₂RR.

The H₂S evolution reaction is a possible dissociation event on Fe₄S₄ clusters.⁷⁵ To test the stability of Ni100–Fe₄S₄, we calculated and plotted the free energy of the H₂SER in Fig. 7b and ESI Table S4.† The calculated thermodynamic energy barrier is quite large $\Delta G = +1.94$ eV, which suggests that the H₂SER on Ni100–Fe₄S₄ is thermodynamically difficult and the reduction of Fe₄S₄ to Fe in metallic form is more difficult. Therefore, the analysis results of side reactions demonstrate that the Ni100–Fe₄S₄ catalyst is promising as a cathode material for the CO₂RR with high selectivity and faradaic efficiency.

4. Conclusion

In conclusion, we propose a strategy for the bio-inspired design approach of CO₂RR catalysts at the atomic level. Taking Ni100–Fe₄S₄ as an example, we designed this heterogeneous single-cluster catalyst by imitating the spatial structure of the Fe–Ni active center in CO dehydrogenase II from *Carboxythermus hydrogenoformans*. We found that Ni100–Fe₄S₄ exhibits a stronger CO₂ activation ability than natural CO dehydrogenase by analyzing the changes in the CO₂ adsorption state, geometric structure and electronic structure. This excellent CO₂ activation ability of Ni100–Fe₄S₄ is mainly attributed to the Fe–Ni site designed by the bio-inspired strategy, forming a Fe–Ni ‘electro-bridge’ enhanced CO₂ activation. The detailed electronic structure analysis shows that the electrons from the Fe–Ni site’s d orbitals partially transfer to the empty π^* orbitals of CO₂, leading to partial occupation of the formed

d- π^* orbitals. Moreover, the free energy changes (ΔG) of the entire CO₂ reduction catalytic cycles were calculated. A detailed study on the reaction mechanism of CO₂ electroreduction shows that CO₂RR on Ni100–Fe₄S₄ follows the circulation pathway of $* \rightarrow CO_2^* \rightarrow COOH^* \rightarrow CO^* \rightarrow CHO^* \rightarrow CH_2O^* \rightarrow CH_3O^* \rightarrow O^* \rightarrow OH^* \rightarrow H_2O^* \rightarrow *$, with the final products of CH₄ and H₂O. To be more rigorous, the side reactions involving the hydrogen evolution reaction (HER) and the H₂S evolution reaction (H₂SER) were also performed and proved to be thermodynamically unfavorable. These promising results show the feasibility of using a Ni100–Fe₄S₄ catalyst as the cathode for the CO₂RR with high selectivity and faradaic efficiency. Therefore, bio-inspired strategies as a transformative approach can be directly applied to heterogeneous catalysts. The clever use of these bio-inspired strategies in modern catalyst design will lead our catalysts beyond their current limitations exploring the final frontier of catalysis.

Author contributions

Hengyue Xu: conceptualization, data curation, formal analysis, investigation, methodology, and writing – original draft. Daqin Guan: formal analysis and writing – review & editing. Lan Ma: project administration, resources, and supervision.

Conflicts of interest

The authors declare no competing interests.

Acknowledgements

This research was funded by the Institute of Biomedical Health Technology and Engineering, Shenzhen Bay Laboratory. We are grateful to the Shenzhen Bay Laboratory Supercomputing Center for providing the high performance computing platform.

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