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Unlocking OER catalytic potential and chiral Fe₃O₄ film as a game-changer for electrochemical water oxidation pathway and by-product control†

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Electrochemical water splitting is an attractive technique for hydrogen production, but its development is constrained due to the sluggish kinetics of the oxygen evolution reaction (OER), limited charge transmission efficiency, and the generation of harmful by-products (like hydrogen peroxide) accompanying the OER process. Herein, we constructed an Fe₃O₄ film with an inherent chiral structure to demonstrate its chiral induced spin selectivity (CISS) effect on modulating the OER pathway and facilitating the transfer of electrons extracted from the OER. Compared with normal Fe₃O₄, the chiral Fe₃O₄ film facilitated the OER pathway for 3 \sum O₂ production via the CISS-induced spin alignment of electrons and radicals, while it suppressed the $\frac{5}{2}$ pathway for peroxide by-product generation. Meanwhile, as a half-metallic material, chiral Fe₃O₄ film promoted the transportation of spin-aligned electrons derived from water oxidation to an external circuit. Compared with normal Fe₃O₄ film which is not capable of aligning electrons, the potential at 10 mA cm⁻² declined by 150 mV, the Tafel slope decreased by 104 mV dec⁻¹, the charge transfer resistance decreased by 50%, the free charge carrier density was amplified by 10-fold, and the electron lifetime was prolonged within the chiral Fe₃O₄ film.

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1. Introduction

For decades, the excessive consumption of fossil fuels has led to severe environmental pollution and a global energy crisis, posing a significant threat to the future development of human society.^{1–5} Consequently, there is an imperative to explore clean and sustainable energy sources capable of replacing fossil fuels. Among these alternatives, hydrogen has garnered considerable attention due to its status as an environmentally friendly energy carrier, characterized by high enthalpy and absence of carbon emissions (such as CO and CO₂) during combustion.^{6–8}

Electrocatalytic water splitting has emerged as a cost-effective and promising technique for generating hydrogen from water, and it offers the advantage of not requiring extreme conditions like high temperature or pressure.^{9–13} A myriad of advanced catalysts for splitting water have been developed, such as MOF-derived catalysts,¹⁴ nickel oxide and nickel phosphide,¹⁵ NiFe selenide,¹⁶ CoNi hydrogen phosphate

nanotubes,¹⁷ nickel nitride,¹⁸ and 2D-layered catalysts like NiCo hydroxide nanosheets.¹⁹

However, the efficiency of electrochemical water splitting falls short of expectations.^{20–23} The primary hurdle in this process lies in the sluggish oxygen evolution reaction (OER) that involves a complex four-electron process.^{24–28} Furthermore, an undesirable by-product, hydrogen peroxide, tends to form at the anodes when electrons derived from water oxidation are not spin-polarized. The presence of this by-product poses a detrimental impact on the OER reaction system, as it tends to poison the surface of electrocatalysts, thereby diminishing their catalytic activity and shortening their operational lifespan.^{29–31} To facilitate efficient water splitting, it has become imperative to accelerate OER kinetics while mitigating the production of hydrogen peroxide by-products during the OER process.

It is noted that the OER is inherently spin-sensitive, because prior to the formation of O=O, the active sites must facilitate the extraction of three out of four electrons with identical spin orientations. Consequently, electrocatalysts that are capable of ensuring spin selectivity at the catalyst/electrolyte interface and subsequently facilitating the seamless transport of these spin-aligned electrons to the external circuit have become highly desirable for enhancing OER efficiency.^{23–25,32,33}

The chiral induced spin selectivity (CISS) effect represents a promising approach to spin control in the OER process.

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For example, the attachment of organic chiral molecules (such as proteins or DNA) to semiconductors like TiO₂ or CdSe, induces a CISS effect, reducing the OER barrier while suppressing the formation of by-products.^{26,27,34} Similarly, Inorganic materials characterized by intrinsic chiral configurations, such as chiral CuO and chiral Co_xO, have showcased the CISS effect on lowering the OER barrier and mitigating the generation of by-products. Notably, their current density can surpass that achieved with semiconductors decorated with organic chiral molecules by up to 1000-fold.^{35–37}

As an inorganic material, magnetite (Fe₃O₄) is renowned for its exceptional catalytic activity resulting from its redox characteristics, narrow band gap, cost-effectiveness, low toxicity, and remarkable durability.^{38,39} It is plausible that incorporating Fe₃O₄ with an inherent chiral structure could lead to a CISS effect on spin control for the OER. Beyond these benefits, Fe₃O₄ stands out as a half-metallic material, exhibiting nearly 100% spin polarization in the electronic density of states (DOS) near the Fermi energy level. Consequently, the electrical conductivity of Fe₃O₄ is fundamentally dependent upon the spin states of electrons, with one spin channel exhibiting metallic behavior, while the other spin channel demonstrates insulating properties.^{40–45} Such a distinguished feature holds potential for enhancing the transfer of spin-aligned electrons from the catalyst to the external circuit.

To verify these hypotheses, we constructed an Fe₃O₄ film with an inherent chiral structure to investigate its CISS effect on spin alignment for the OER and its effectiveness in transferring spin-aligned electrons to the external circuit. We observed that, compared with normal Fe₃O₄ film without a chiral structure, the utilization of a chiral Fe₃O₄ film as an OER electrocatalyst resulted in notable catalytic improvements, encompassing the facilitation of the OER pathway while hindering hydrogen peroxide by-products, a 150 mV reduction in the applied potential required to achieve 10 mA cm⁻², a 42% increase in current density at 1.8 V (*vs.* SCE), a decrease of 104 mV dec⁻¹ in the Tafel slope, a 50% reduction in charge transfer resistance, and a 10-fold amplification in the free charge carrier density. The benefits brought about by the chiral Fe₃O₄ film are intricately

intertwined with the CISS effect induced by its chiral structure and the capabilities of half-metallic materials to facilitate electron transfer.

2. Results and discussion

Fig. 1(a) shows the XRD patterns of the chiral Fe₃O₄ film coated on FTO by electrochemical deposition. (Details are provided in ESI†). The XRD patterns exhibit diffraction peaks corresponding to SnO₂ (JCPDS 2-1337) and Fe₃O₄ (JCPDS 7-322). The intensity of the Fe₃O₄ diffraction peak is lower than that of SnO₂, due to the relatively small amount of Fe₃O₄ on the FTO substrate. The XPS spectra were acquired to delve into the surface state of chiral Fe₃O₄ on FTO. In Fig. 1(b), the XPS survey spectra reveal that the surface of chiral Fe₃O₄ is primarily composed of Fe and O elements. The chiral Fe₃O₄ film has a regular laminate morphology, as demonstrated in Fig. 2(a). Furthermore, the laminate structure of chiral Fe₃O₄ is hierarchically constructed from nanoparticles, as Fig. 2(b) shows.

The Fe 2p XPS spectrum of the chiral Fe₃O₄ film is presented in Fig. 3. Within this spectrum, the binding energy peak centered at approximately 710.6 eV corresponds to the Fe 2p_{3/2} state, while the peak at 724.0 eV corresponds to the Fe 2p_{1/2} state.^{46–49} These peaks are fitted using a shakeup satellite and two spin-orbit doublets, which originate from the Fe³⁺ and Fe²⁺ states.^{46–48} The area ratio of Fe³⁺/Fe²⁺ in the spectrum is approximately 2, indicating that the material deposited on the FTO substrate is Fe₃O₄.

The chirality of the catalyst surface was assessed through an electrochemical selectivity test, a sensitive technique for discerning the surface chirality of materials (details in ESI†).^{50,51} As shown in Fig. 4(a), chiral Fe₃O₄ exhibited a higher current density and smaller reduction potential when it was scanned in a chiral electrolyte comprising 10 mM L-tartaric acid than in a chiral electrolyte containing 10 mM D-tartaric acid. These results confirmed that chiral Fe₃O₄ exhibited contrasting chiral selectivity responses in electrolytes with opposite chirality, specifically preferring charge exchanges with L-tartaric acid.

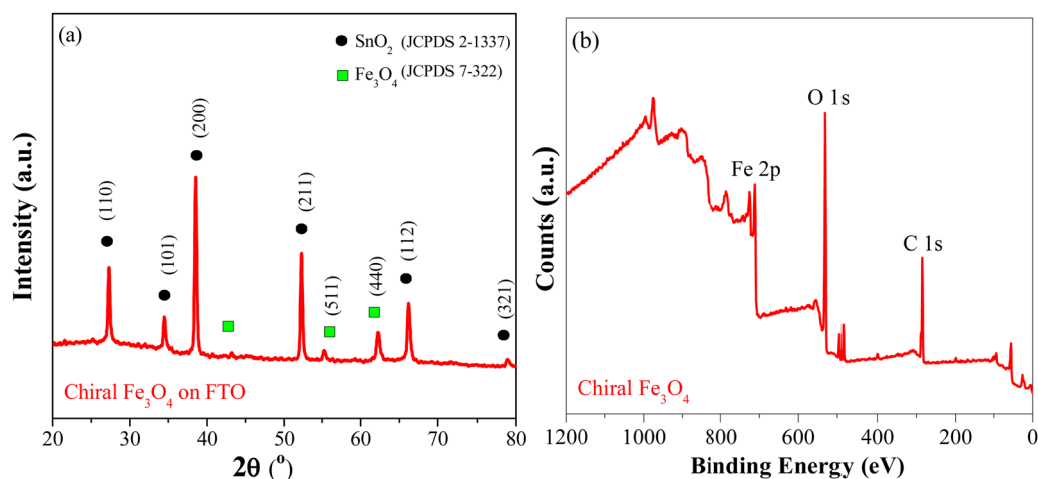


Fig. 1 (a) XRD patterns and (b) XPS survey spectra (b) of chiral Fe₃O₄.



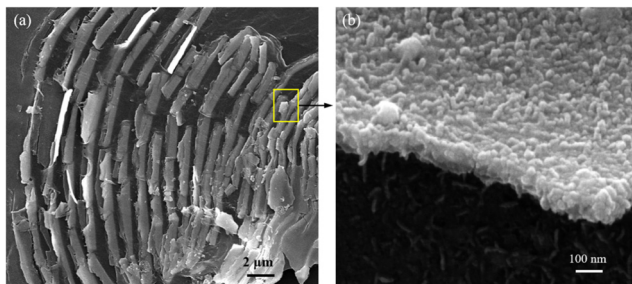


Fig. 2 (a) SEM image of chiral Fe_3O_4 ; (b) magnification image of the rectangular region in (a).

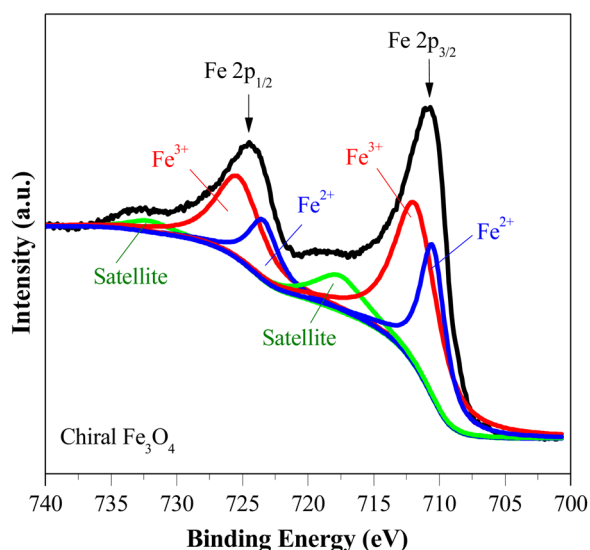


Fig. 3 Fe 2p XPS spectra of chiral Fe_3O_4 .

To complement the findings from the electrochemical selectivity test, we further elucidated the surface chirality of the chiral Fe_3O_4 film using circular dichroism spectroscopy (CD) and polarized optical microscopy (POM) measurements performed in reflection mode. Fig. 4(b) demonstrates that the chiral Fe_3O_4 film prominently displays optical activity within the visible light region, whereas normal Fe_3O_4 exhibits no discernible optical activity within this region, suggesting inherent chirality with the chiral Fe_3O_4 film. This observation strongly implies the intrinsic chirality of the chiral Fe_3O_4 film. The results of POM are shown in Fig. S2 (ESI[†]), which also support the formation of a chiral film.

The chiral Fe_3O_4 film, which has inherent chiral structure, demonstrated a CISS effect on spin alignment during the OER. This was verified by monitoring the generation of the singlet-state by-product H_2O_2 throughout the OER process.^{32–34} The UV-vis spectra of the electrolyte in the water oxidation system are presented in Fig. 5(a), employing *o*-tolidine as an indicator to track the production of H_2O_2 . When normal Fe_3O_4 was used as an electrocatalyst, an absorption peak emerged at approximately 436 nm, as H_2O_2 oxidized *o*-tolidine, leading to the formation of a yellow compound. However, this peak was substantially diminished when the chiral Fe_3O_4 film was utilized as an electrocatalyst, signifying the inhibition of H_2O_2 generation alongside OER.

As depicted in Fig. 5(b), the OER pathway of Fe_3O_4 in alkaline media follows the adsorbate evolution mechanism (AEM), involving a sequential series of concerted four-proton-coupled electron transfer (PCET) processes that take place on active sites. These processes create multiple oxygen intermediates, including $^*\text{OH}$, $^*\text{O}$, and $^*\text{OOH}$, to establish the pathway, $^*\text{OH} \rightarrow ^*\text{O} \rightarrow ^*\text{OOH} \rightarrow \text{O}_2$ for the formation of O_2 . It is recognized that the OER process is spin sensitive, because the four electrons extracted from its four steps should have the same spin direction before the formation of the $\text{O}=\text{O}$ bond.

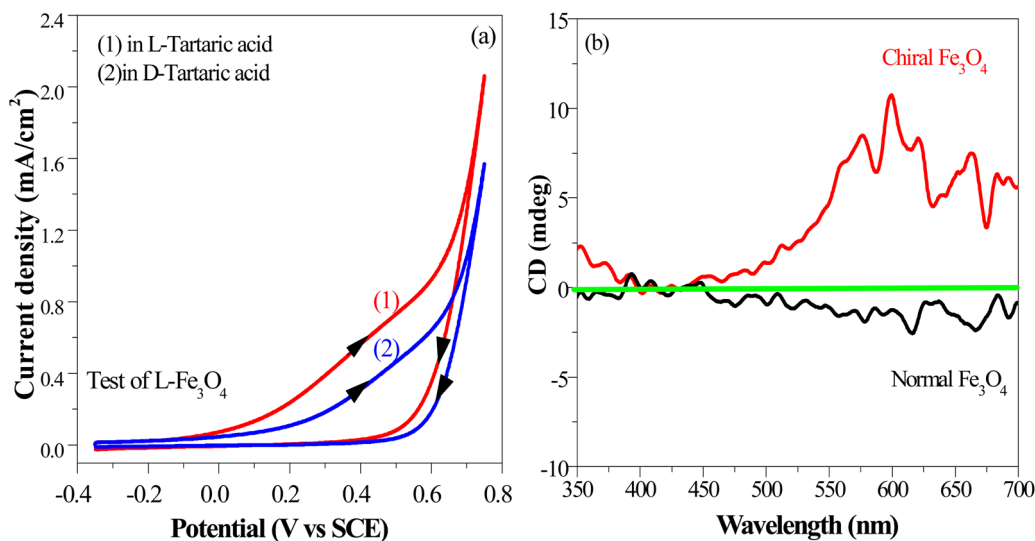


Fig. 4 (a) Electrochemical selectivity test for chiral Fe_3O_4 (scanned in a chiral electrolyte involving 10 mM L-tartaric acid and in another chiral electrolyte involving 10 mM D-tartaric acid; arrows indicate scan direction). (b) CD spectra of the chiral Fe_3O_4 film and normal Fe_3O_4 film.



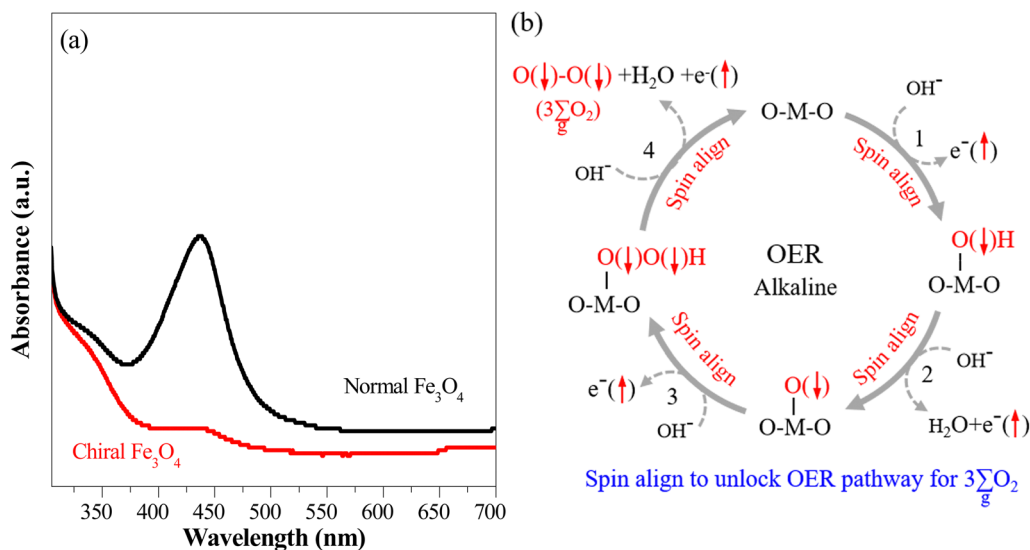


Fig. 5 “ $3 \sum_g \text{O}_2$ ” (a) Visible absorption spectra for the utilized electrolyte titrated with *o*-tolidine as an indicator to assess H₂O₂ by-product formation in systems employing the chiral Fe₃O₄ and normal Fe₃O₄ films as electrocatalysts. (b) Scheme for the CISS effect of chiral Fe₃O₄ on facilitating the water oxidation pathway of $3 \sum_g \text{O}_2$ formation and forbidding the production of H₂O₂ during the OER in alkaline electrolyte.

Thereby, the spin orientations of electrons and radicals are beneficial for delivering $3 \sum_g \text{O}_2$.

The inhibition of H₂O₂ by-product suggests that the chiral Fe₃O₄ film filtered the spin orientation of electrons acquired from water oxidation through the CISS effect,^{29,30,32,33} synchronously ensuring the alignment of spins in the newly generated •OH radicals that subsequently attached to the M sites of O–M–O species on the Fe₃O₄ surface during step 1 and step 3 of the AEM process, as demonstrated in Fig. 5(b). This facilitated the

water oxidation pathway for the formation of the triplet-state product, $3 \sum_g \text{O}_2$ while promoting the alignment of electrons

extracted from water oxidation throughout the four steps of AEM. Conversely, the formation of H₂O₂, which occurs on the singlet potential energy surface, was hindered.^{29,30,33}

In accordance with the CISS-induced preference for the $3 \sum_g \text{O}_2$ formation pathway during the OER, chiral Fe₃O₄ exhibited a lower water oxidation barrier than normal Fe₃O₄. As

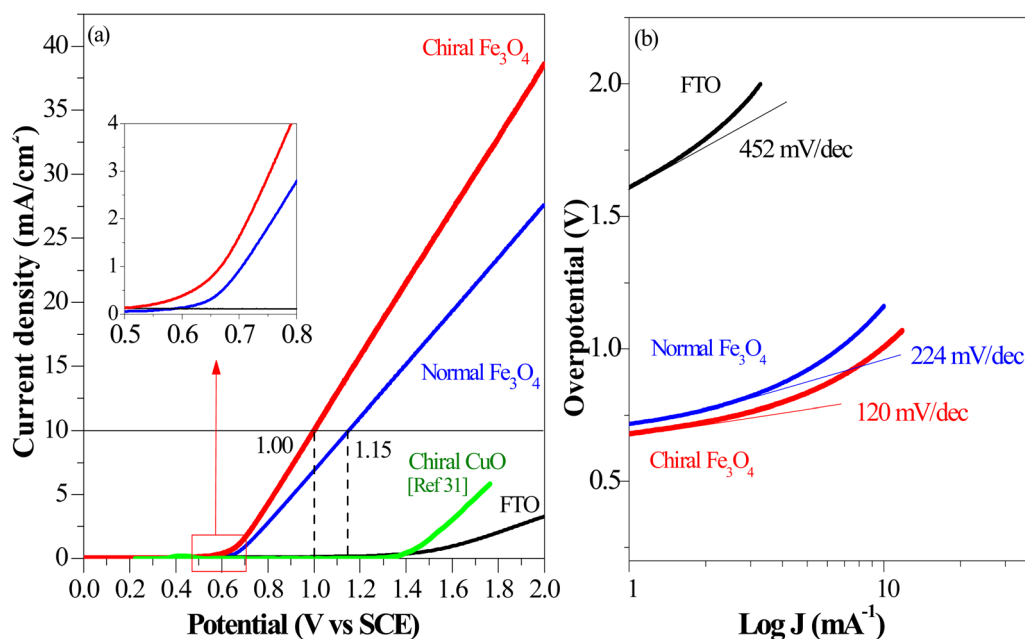


Fig. 6 (a) Linear sweep voltammetry characterization of chiral Fe₃O₄, normal Fe₃O₄, FTO, and chiral CuO (the LSV of chiral Fe₃O₄, normal Fe₃O₄, and FTO were recorded in 0.1 M KOH as electrolyte at room temperature with calomel as reference; the LSV of chiral CuO refers to ref. 31).



depicted in the inset of Fig. 6(a), the LSV onset potential was reduced in comparison with normal Fe₃O₄. Additionally, the potential required to achieve a current density of 10 mA cm⁻² decreased by 150 mV when the chiral Fe₃O₄ film was used as an electrocatalyst.

As mentioned above, being a half-metallic material, Fe₃O₄ should be fundamentally efficient for transferring spin-aligned electrons, even displaying metallic behavior. Here, it is noticed that the chiral Fe₃O₄ and normal Fe₃O₄ films demonstrated superior performance in OER current density compared to the chiral CuO film, which is not a half-metal, as shown in Fig. 6(a).

In addition, as seen in Fig. 6(a), the current density generated by the chiral Fe₃O₄ film at 1.8 V (vs. SCE) was 42% higher than that of normal Fe₃O₄, indicating that the chiral Fe₃O₄ film facilitated electron transfer compared to normal Fe₃O₄ film. Furthermore, as shown in Fig. 6(b), the Tafel slope of the chiral Fe₃O₄ film was 104 mV dec⁻¹ smaller than that of normal Fe₃O₄, which suggests that the presence of chirality on the Fe₃O₄ film enhances OER kinetics and carrier transport. These results demonstrate that, in addition to its CISS effect in promoting the OER pathway for 3 ∑_g O₂ production, the chiral

Fe₃O₄ film facilitates a more efficient transfer of spin-aligned electrons, derived from water oxidation, from the catalyst to the external circuit compared to the normal Fe₃O₄ film.

In line with the findings from LSV and Tafel characterization, the results from electrochemical impedance spectroscopy (EIS) reveal that the chiral Fe₃O₄ film exhibited smaller Nyquist circle diameters than normal Fe₃O₄ (see Fig. 7(a)). To gain further insights from these Nyquist plots, we employed an R(RQ) circuit model for fitting, and the fitting outcomes are summarized in Table 1. Herein, R_Ω represents solution resistance, Q_d denotes electrochemical double-layer capacitance, and R_{ct} corresponds to charge transfer resistance. The R_{ct} value for normal Fe₃O₄ was only 6% of that observed for FTO,

Table 1 Simulation data of chiral Fe₃O₄, normal Fe₃O₄ and FTO with equivalent circuit R(QR)

	R _Ω (Ω)	Q _d (×10 ⁻⁴ F)	n	R _{ct} (Ω)
Fe ₃ O ₄	42.95	0.2823	0.9434	3.314 × 10 ⁵
Chiral Fe ₃ O ₄	33.48	1.122	0.95	1.369 × 10 ⁵
FTO	36.45	0.08913	0.9642	5.135 × 10 ⁶

suggesting the significance of Fe₃O₄ in promoting electron transfer for the OER. Notably, the chiral Fe₃O₄ film exhibits a remarkable 50% reduction in R_{ct} compared to normal Fe₃O₄, suggesting that electron transport across Fe₃O₄ was enhanced due to its intrinsic chiral structure.

Simultaneously, Mott-Schottky measurements provided further evidence of the pivotal role played by chirality in enhancing the catalytic activity of Fe₃O₄ film in the OER. The Mott-Schottky equation, expressed as (C_{sc})⁻² = 2(E - E_{fb} - kT/e)/(εε₀A²eN_d) (details in ESI[†]), dictates that the slope of the linear segments in the Mott-Schottky plot correspond to 2/(εε₀A²eN_d).^{52,53} These linear segments are associated with the depleted states of majority carriers located within the space charge region.⁵⁴ As depicted in Fig. 7(b), the slope of the linear segment of normal Fe₃O₄ was approximately 2.03, while the slope of the chiral Fe₃O₄ film was around 0.19, merely 10% of that observed for normal Fe₃O₄. It is calculated that the charge carrier density (N_d) of normal Fe₃O₄ was about 3.5 × 10²⁸ cm⁻³, while for the chiral Fe₃O₄ film, it was approximately 3.7 × 10²⁹ cm⁻³. This result shows that the majority carrier density within the space charge region of Fe₃O₄ increased up to 10-fold due to the incorporation of chirality.

Furthermore, evidence from the Bode and phase angle plots serves to reinforce the enhanced electron transport capabilities observed in the chiral Fe₃O₄ film. In Fig. 8(a), the Bode plots illustrate that the chiral Fe₃O₄ film displays lower impedance modulus values compared to normal Fe₃O₄ and FTO. This

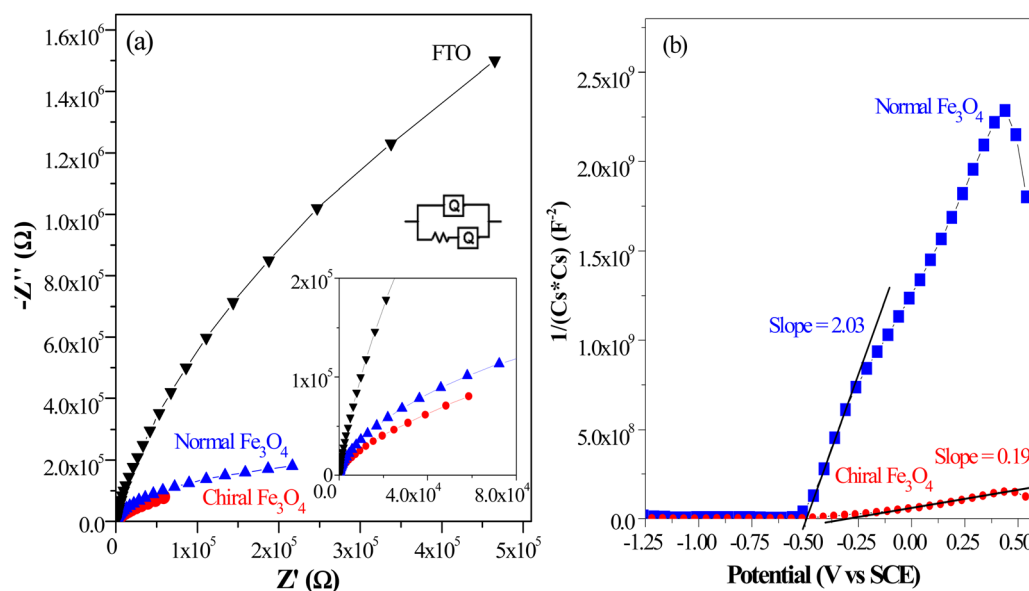


Fig. 7 (a) Nyquist plots of L-Fe₃O₄, D-Fe₃O₄, normal Fe₃O₄ and FTO. (b) Mott-Schottky plots of L-Fe₃O₄, D-Fe₃O₄ and normal Fe₃O₄.



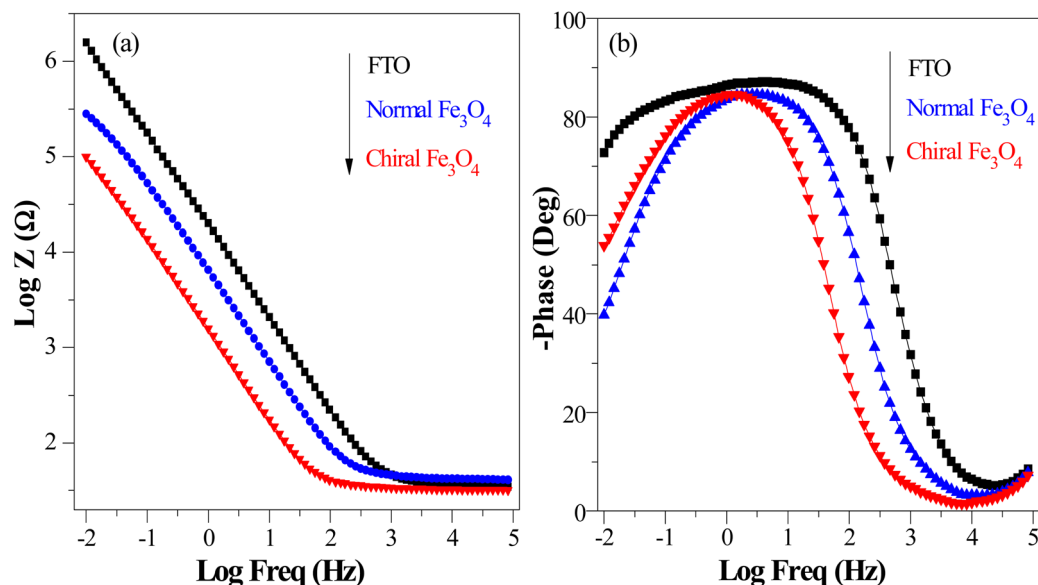


Fig. 8 (a) Bode plots of chiral Fe₃O₄ film and normal Fe₃O₄ and FTO. (b) Phase angle plots of chiral Fe₃O₄ film and normal Fe₃O₄ and FTO.

observation signifies an increase in carrier mobility on the chiral Fe₃O₄ film.⁵⁵ Moreover, as depicted in Fig. 8(b), the phase angle plot for chiral Fe₃O₄ shifts towards lower frequencies compared to normal Fe₃O₄. This red shift indicates accelerated carrier mobility across the chiral Fe₃O₄ film. Furthermore, Fig. 8(b) also reveals that the electron lifetime within the chiral Fe₃O₄ film is prolonged compared to that within the normal Fe₃O₄ film, taking into account that the electron lifetime (τ_e) can be calculated with the equation $\tau_e = 1/2\pi f_{\max}$, where f_{\max} represents the peak frequency.^{49,56}

The elongated electron lifetime implies lower charge recombination probability in chiral Fe₃O₄ film than in normal Fe₃O₄ film.

Additionally, hydrogen production in water splitting systems with different OER catalysts was demonstrated, as shown in Fig. 9(a) with chiral Fe₃O₄ film and normal Fe₃O₄ film as OER catalysts. The hydrogen production rate with chiral Fe₃O₄ film as OER catalyst was approximately 20% higher than that with normal Fe₃O₄ film as OER electrocatalyst and about 5 times of that with chiral CuO film as OER electrocatalyst. Furthermore,

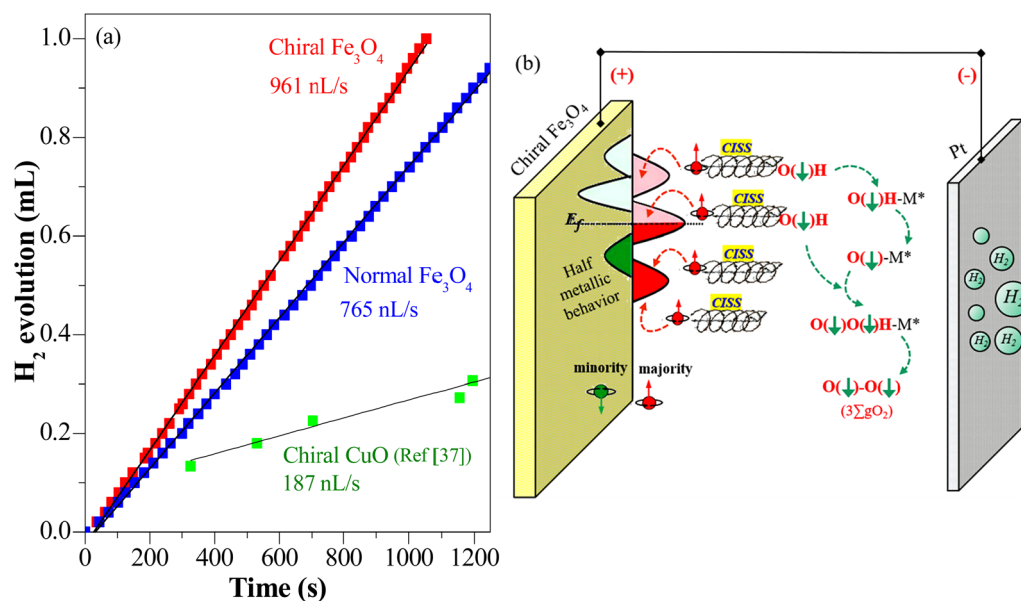


Fig. 9 (a) Hydrogen production recorded in a water splitting system with chiral Fe₃O₄ and normal Fe₃O₄ as OER catalysts (conducted at a voltage of 1.5 V (vs. SCE) in 0.1 M KOH electrolyte, at room temperature, with calomel as reference, Pt wire as counter). The hydrogen production of chiral CuO refers to ref. 37. (b) Scheme of the CISS effect in conjunction with the half-metallic nature of chiral Fe₃O₄ film for aligning the spins of electrons and radicals for the OER and the transportation of spin-oriented electrons.



chiral Fe₃O₄ film exhibited robust electrocatalytic activity during the three experimental trials, as shown in Fig. S1 (ESI†). In each trial, the hydrogen production rate was enhanced by at least 20% when chiral Fe₃O₄ was employed as electrocatalyst rather than normal Fe₃O₄ as electrocatalyst. The growth of the hydrogen production rate is associated with the elevation of water oxidation kinetics and decline of the OER barrier, which was induced by the chiralization of the Fe₃O₄ catalyst. The stability also suggests the robustness of the chiral Fe₃O₄ film for the OER, as shown in Fig. S4 (ESI†).

The evidence presented above coherently demonstrates the advantages offered by the chiral Fe₃O₄ film compared to normal Fe₃O₄ film and chiral CuO. As illustrated in Fig. 9(b), during the OER, the CISS effect of the chiral Fe₃O₄ film aligned the spins of electrons and radicals. This spin-controllable process improved the possibility for the formation of the triplet-state product $3 \sum_g \text{O}_2$, promoted the AEM water oxidation pathway, and thereby reduced the barrier for the OER. Meanwhile, the half-metallic nature of Fe₃O₄ facilitated the transfer of spin-aligned electrons. The combined and synergistic influence of these factors plays a pivotal role in unlocking the catalytic potential of Fe₃O₄ film for the OER.

3. Conclusion

In summary, this work demonstrated a strategy that harnesses the synergy of chirality and half-metallic materials for unlocking the electrochemical catalytic potential of the OER. Though the current density enhancement of chiral Fe₃O₄ over normal Fe₃O₄ is not too high, it provides a promising way to facilitate the OER pathway towards $3 \sum_g \text{O}_2$ production through the CISS-induced spin control during AEM. When contrasted with normal Fe₃O₄ film which lacks the capability to align electrons, the chiral Fe₃O₄ film suppressed the pathway of H₂O₂ by-product formation, decreased the potential required to obtain 10 mA cm⁻² current density by 150 mV, reduced the Tafel slope by 104 mV dec⁻¹, elevated the current density by 42% at 1.8 V (vs. SCE), lowered the charge transfer resistance by 50%, achieved a 10-fold amplification of the free charge carrier density, and extended the electron lifetime within the catalyst. Furthermore, chiral Fe₃O₄ exhibited enhanced OER performance over chiral CuO as the transfer of spin-aligned electrons extracted from water oxidation to the external circuit was promoted due to the half-metallic nature of Fe₃O₄.

Notes

Experimental details and characterization details of this work are shown in our ESI.†

Data availability

The data that supports the findings of this study are available within the article and its supplementary material. No additional data are available.

Author contributions

Wenyan Zhang: conceptualization, supervision, writing – reviewing and editing, investigation, project administration, funding acquisition. Chaoqun Jiang: conceptualization, methodology, writing – reviewing and editing, investigation. Hangmin Guan: conceptualization, methodology, writing – reviewing and editing, investigation. Yuanyuan Wang: methodology, investigation, writing – original draft, funding acquisition. Yingfei Hu: methodology, investigation, writing – original draft, funding acquisition. Wei Wang: formal analysis, investigation. Wenjie Tian: visualization, formal analysis. Lingyun Hao: formal analysis, writing – original draft.

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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