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Construct Fe^{2+} species and Au particles for significantly enhanced photoelectrochemical performance of $\alpha\text{-Fe}_2\text{O}_3$ by ion implantation

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ABSTRACT Photoelectrochemical (PEC) water splitting is a promising approach to producing H_2 and O_2 . Hematite ($\alpha\text{-Fe}_2\text{O}_3$) is considered one of the most promising photoelectrodes for PEC water splitting, due to its good photochemical stability, non-toxicity, abundance in earth, and suitable bandgap ($E_g \sim 2.1$ eV). However, the PEC water splitting efficiency of hematite is severely hampered by its short hole diffusion length (2–4 nm), poor conductivity, and ultrafast recombination of photogenerated carriers (about 10 ps). Here, we show a novel and effective method for significantly improving the PEC water splitting performance of hematite by Au ion implantation and the following high-temperature annealing process. Based on a series of characterizations and analyses, we have found Fe^{2+} species and tightly attached Au particles were produced at Au-implanted hematite. As a result, the charge separation and charge injection efficiency of Au-implanted Fe_2O_3 are markedly increased. The photocurrent density of optimized Au-implanted Fe_2O_3 could reach 1.16 mA cm^{-2} at 1.5 V vs. RHE which was nearly 300 times higher than that of the pristine Fe_2O_3 ($4 \mu\text{A cm}^{-2}$). Furthermore, the Au-implanted Fe_2O_3 photoelectrode exhibited great stability for the 8-hour PEC water splitting test without photocurrent decay.

Keywords: hematite, Fe^{2+} species, photoelectrochemical water splitting, ion implantation

INTRODUCTION

Energy and pollution problems have attracted more and more attention in modern society. It is necessary and unavoidable to adjust the energy structure by replacing traditional fossil energy with renewable energy. Photo-

electrochemical (PEC) water splitting is a promising approach to producing H_2 and O_2 [1]. Since Fujishima and Honda [2] firstly used TiO_2 as a photoelectrode to produce H_2 and O_2 under UV illumination, many kinds of semiconductors like $\alpha\text{-Fe}_2\text{O}_3$, C_3N_4 , BiVO_4 , etc. have been intensively researched as potential photoelectrodes [3–8]. Even though many efforts have been made to improve the PEC water splitting performance of these photoelectrodes, the real efficiency is still far below the theoretical calculation value [9–11].

Among these materials, hematite ($\alpha\text{-Fe}_2\text{O}_3$) is considered as one of the most promising photoelectrodes for PEC water splitting, due to its good photochemical stability, non-toxicity, abundance in earth, and suitable bandgap for PEC water splitting ($E_g \sim 2.1$ eV) [9]. However, hematite is a kind of Mott insulator [12,13], so that the PEC performance of hematite is severely hampered by its short hole diffusion length (about 2–4 nm), poor conductivity and ultrafast recombination of photogenerated carriers (about 10 ps) [9]. Different strategies were developed to deal with those problems, including: (1) doping hematite with heteroatom (Sn, Ti, Si, etc.) to improve free carrier density [14–18]; (2) controlling morphology to shorten transfer distance of carriers, hematites with various morphology, such as nanowires, nanotubes, and nanoporous films were synthesized and exhibited improved performances [17–20]; (3) introducing self-doped Fe^{2+} species to improve the conductivity of hematite [21–25]; (4) combining with the noble metal (Au, Pt, etc.) to improve the surface charge separation efficiency [24–28]. Although many novel and excellent PEC systems have been designed and exhibited improved

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performances, an effective and scalable preparation method to integrate several strategies is yet to be developed.

Ion implantation has been a typical surface modification technology to tune the electronic properties of semiconductor materials in industry for decades [29]. By accurately controlling the acceleration voltage and implantation dosage, we can uniformly and precisely dope various kinds of materials with heteroatoms to change their electrical and mechanical surface properties. In our previous work, we used ion implantation to fabricate N-doped TiO₂ and realized high-efficiency visible light PEC water splitting [30].

Herein, we report a novel and effective method that improves the PEC water splitting performance of hematite by Au ion implantation and the following high-temperature annealing treatments. Based on a series of characterization and analyses, we have found Fe²⁺ species and Au particles were formed at Au-implanted hematite. Fe²⁺ species and tightly attached Au particles led to a remarkable improvement of photoinduced charge separation and charge injection efficiency. The charge injection efficiency was greatly increased from 2% (pristine Fe₂O₃) to 89% (optimized Au-implanted hematite) at 1.5 V vs. reversible hydrogen electrode (RHE). Therefore, the photocurrent density was enhanced by nearly 300 times, and the incident photon-to-current conversion efficiency (IPCE) of optimized Au-implanted hematite can reach 25.8% at 350 nm, which is much higher than the IPCE value of pristine Fe₂O₃ (0.57%). In addition, Au-implanted Fe₂O₃ photoelectrode exhibited excellent stability in the 8-hour PEC testing.

EXPERIMENTAL SECTION

Preparation of Fe₂O₃ and Au-implanted Fe₂O₃

Akaganeite (β -FeOOH) was first grown on a fluorine-doped tin oxide glass (FTO) using a reported hydrothermal method [31]. In a typical experiment, 1.378 g ferric chloride (FeCl₃·6H₂O) and 2.89 g sodium nitrate (NaNO₃) were added to 34 mL deionized water and the mixture was magnetically stirred for 5 min. Then the aqueous solution was adjusted to pH 1.5 with HCl and further subjected to magnetic stirring for another 10 min. The precursor solution was added to a 50-mL Teflon-lined stainless steel autoclave. A piece of FTO glass slide, having been washed with acetone, ethanol, and deionized water and blown dry quickly with N₂ air, was put into the autoclave where it was heated at 95°C for 4 h in an oven and naturally cooled down to ambient temperature. Then

a uniform yellow layer of β -FeOOH could grow on FTO glass substrate. It was taken out and washed with deionized water and blown dry quickly with air. Subsequently, Au ions were implanted into β -FeOOH at 30 kV with different ion dosages (1×10^{16} , 2.5×10^{16} , 5×10^{16} , 1×10^{17} ions cm⁻²) by metal vapor vacuum arc (MEVVA) ion source implanter. Finally, pristine β -FeOOH and Au-implanted β -FeOOH were annealed in air at different temperatures for 2 h in a horizontal quartz-tube furnace.

Characterization of Fe₂O₃ and Au-implanted Fe₂O₃

The field-emission scanning electron microscopy images (FE-SEMs) were collected by JEOL S-4800 (Japan). X-ray diffraction (XRD) was carried out on Bruker AXS, D8 Advance X-ray powder diffractometer with Cu-K α radiation ($\lambda=0.15418$ nm, Germany). Raman measurements were performed by laser confocal micro Raman spectrometers (Renishaw inVia, Renishaw, UK) with laser excited at 488 nm. X-ray photoelectron spectroscopy (XPS) measurements were done on a Thermo Scientific ESCA-LAB 250 Xi system (USA) with Al K α (1486.6 eV) as the radiation source and all spectra were calibrated using the C 1s peak with a value of 284.8 eV. The UV-vis absorption spectra were collected by SHIMADZU UV-2550 UV-vis spectrophotometer. Mossbauer spectroscopy was performed at room temperature by a RiKon-5A (Germany) proportional counter with gas mixture of 96% He and 4% CH₄. A ⁵⁷Co in Rh matrix source with activity of 25 mCi (1 mCi=37×10⁶ Bq) was used for excitation.

Photoelectrochemical measurements

PEC measurements of the hematite photoanodes were carried out in a conventional three-electrode electrochemical cell using Pt wire as the counter electrode and Ag/AgCl electrode as the reference electrode. A solution of 1.0 mol L⁻¹ NaOH (pH 13.6) was used as the electrolyte (purged with Ar). All linear sweep voltammograms were measured by a computer-controlled electrochemical workstation (CHI 650E) under a 500 W xenon lamp with an AM 1.5 global filter at an irradiation intensity of 100 mW cm⁻². IPCE spectra were obtained by using a xenon lamp (Newport model 66902) coupled with a grating monochromator (Newport Model 74125) and a power meter (Newport model 2936-R) in the wavelength range from 300 to 650 nm at an applied potential of 1.5 V (vs. RHE). The charge separation efficiency was measured under 458 nm monochromatic light and H₂O₂ was used as the hole scavenger in the electrolyte. The charge injection efficiency was measured by using the H₂O₂ as the hole scavenger in the electrolyte [27].

Figure 1 The top view and cross-sectional SEM images of β -FeOOH annealed at 550°C for 2 h (pristine Fe_2O_3) (a–c), Au ion implanted β -FeOOH at 30 kV with 5×10^{16} ions cm^{-2} and annealed at 550°C for 2 h ($\text{Au-Fe}_2\text{O}_3$ -550) (d–f), and Au ion implanted β -FeOOH at 30 kV with 5×10^{16} ions cm^{-2} and annealed at 550°C for 2 h and following at 700°C for further 15 min ($\text{Au-Fe}_2\text{O}_3$ -700) (g–i).

RESULTS AND DISCUSSION

β -FeOOH was synthesized with a hydrothermal method and conducted with Au implantation. Subsequently, the pristine β -FeOOH sample and Au ion implanted akaganeite samples were annealed at 550°C in air for 2 h to be converted into hematite (Fe_2O_3 , $\text{Au-Fe}_2\text{O}_3$ -550). As shown in Fig. 1, FE-SEM was used to characterize the morphology of pristine Fe_2O_3 and Au-implanted Fe_2O_3 . The pristine Fe_2O_3 exhibits smooth and uniform nanorod morphology with a length of 650 nm (Fig. 1a–c). After Au ion implantation and thermal annealing (Fig. 1d, e), the surface of hematite became rougher and more compact. It can be seen clearly that the implanted Au atoms recrystallized and grew to Au particles on the surface and the gaps of hematite [32]. Meanwhile, the thickness of hematite film was reduced to about 400 nm (Fig. 1f), which can be attributed to the fact that the surface hematite layer was sputtered by high energy implanted Au ions [33]. After annealing of Au-implanted Fe_2O_3 at higher temperatures (at 700°C for another 15 min ($\text{Au-Fe}_2\text{O}_3$ -700)), the surface of hematite became macro-granular (Fig. 1g, h). Meantime, the thickness of hematite was further reduced to 360 nm due to the regrowth of hematite [34], and the contact properties between Au

particles and hematite for $\text{Au-Fe}_2\text{O}_3$ -700 are better than those of the $\text{Au-Fe}_2\text{O}_3$ -550 (Fig. 1e, h). Tightly attached Au particles could serve as the charge mediator, and therefore the photogenerated carriers could efficiently and fast transport through the hematite and electrolyte. Furthermore, accompanied by the reduction of hematite thickness, the optical absorption intensities of $\text{Au-Fe}_2\text{O}_3$ -550 and $\text{Au-Fe}_2\text{O}_3$ -700 are weaker than the pristine Fe_2O_3 as shown in Fig. S1.

As illustrated in Fig. 2a, b, Raman and XRD measurements were performed to characterize the composition and crystalline phases of pristine Fe_2O_3 and Au ion implanted Fe_2O_3 ($\text{Au-Fe}_2\text{O}_3$ -550 and $\text{Au-Fe}_2\text{O}_3$ -700). The prominent Raman peaks for pristine Fe_2O_3 (Fig. 2a) correspond to A_{1g} (225 and 498 cm^{-1}) and E_g (247, 293, 299, 412, and 613 cm^{-1}) modes of the crystalline hematite phase, which is consistent with a previous report [35]. Meanwhile, Raman spectra of $\text{Au-Fe}_2\text{O}_3$ -550 and $\text{Au-Fe}_2\text{O}_3$ -700 are same as that of pristine Fe_2O_3 [36], indicating that there is no phase change at Au ion implanted Fe_2O_3 . XRD spectra results also confirmed the conclusion of Raman studies (Fig. 2b) (JCPDS 33-0664) [37]. Moreover, the XRD diffraction peak located at 38.18° (JCPDS 04-0784) indicates that the crystalline Au

Figure 2 (a) Raman spectra of pristine Fe₂O₃, Au-Fe₂O₃-550, Au-Fe₂O₃-700; (b) XRD spectra of FTO, Fe₂O₃, Au-Fe₂O₃-550, and Au-Fe₂O₃-700; XPS Fe 2p (c) and Au 4f (d) spectra of pristine Fe₂O₃, Au-Fe₂O₃-550, Au-Fe₂O₃-700.

phase was produced in Au-Fe₂O₃-550 and Au-Fe₂O₃-700. Impressively, compared with Au-Fe₂O₃-550, after further 700°C annealing treatment, the intensity of hematite (125) peak at 66.02° was obviously enhanced and a new Au (220) peak at 64.58° appeared in the Au-Fe₂O₃-700 sample. The Au (220) peak is very close to the hematite (125) peak, and the lattice mismatch between Au (220) and hematite (125) is only 3.05% [38]. Therefore, the contact properties between Au particles and hematite at Au-Fe₂O₃-700 are much tighter than those of Au-Fe₂O₃-550, which was in agreement with SEM images shown in Fig. 1e, h. The strong contact of noble metal and semiconductor would be beneficial for surface photoinduced charge separation [27,39].

XPS was employed to investigate the chemical composition and the change of chemical state on the surface. The survey spectra of Fe₂O₃, Au-Fe₂O₃-550, and Au-Fe₂O₃-700 were shown in Fig. S2. As shown in Fig. 2c, the two peaks centered at 711.4 and 724.7 eV of pristine Fe₂O₃, Au-Fe₂O₃-550, and Au-Fe₂O₃-700 are corre-

sponding to Fe 2p_{3/2} and 2p_{1/2} of Fe³⁺, respectively [40]. The Fe 2p_{3/2} satellite peaks located at about 719 eV are also attributed to the Fe³⁺ specie [41]. More importantly, the satellite peaks located at 716 eV, which can be attributed to Fe²⁺ species [21], were found in Au-Fe₂O₃-550 and Au-Fe₂O₃-700 samples, but not in pristine Fe₂O₃. This suggests that Fe²⁺ species were produced in Au-Fe₂O₃-550 and Au-Fe₂O₃-700 [21,40]. In order to further analyze the oxidation states of Fe element, Mossbauer measurement was also used to characterize the chemical states of the iron element for Au-Fe₂O₃-550. As shown in Fig. S3, the spectroscopy shows a typical 6-line pattern for hematite. Meanwhile, the Fe²⁺ signal was found after fitting the Mossbauer spectroscopy, which consists with the result of XPS [42,43]. The formation of Fe²⁺ species in Au-implanted hematite can be attributed to the preferential oxygen sputtering during the Au ion implantation [44]. In previous work, it was reported that moderate Fe²⁺ sites could improve the conductivity of hematite and enhance the PEC performance [21,45]. Meanwhile, the

Figure 3 (a) Linear sweep voltammetry curves of pristine Fe₂O₃, Au-Fe₂O₃-550, Au-Fe₂O₃-700 under simulated AM 1.5 G illumination; (b) IPCE spectra collected at 1.5 V vs. RHE; (c) chopped photocurrent *I*-*t* curves under AM 1.5 G illumination of different Au implantation dosages at the same annealing temperature of 550°C for 2 h; (d) photocurrent *I*-*t* curves of Au-Fe₂O₃-700 at 1.5 V vs. RHE for 8 h under simulated AM 1.5 G illumination.

XPS Au 4f core-level spectra were also measured for pristine Fe₂O₃, Au-Fe₂O₃-550, and Au-Fe₂O₃-700 (Fig. 3d). The peaks located at 83.7 and 87.3 eV are consistent with Au⁰ 4f_{7/2} and 4f_{5/2} peaks [46].

PEC measurements of the hematite photoanodes were carried out in a conventional three-electrode electrochemical cell using Pt wire as the counter electrode and Ag/AgCl electrode as the reference electrode. A 1 mol L⁻¹ NaOH solution (pH 13.6) was used as the electrolyte. The measured potentials vs. Ag/AgCl were converted to a RHE scale according to the Nernst equation [47]:

$$E_{\text{RHE}} = E_{\text{Ag/AgCl}} + E_{\text{Ag/AgCl}}^0 + 0.059 \times \text{pH},$$

where $E_{\text{Ag/AgCl}}^0 = 0.1976$ V at 25°C, $E_{\text{Ag/AgCl}}$ is the experimentally measured potential against the Ag/AgCl reference electrode, and E_{RHE} is the converted potential vs. RHE. Linear sweep voltammetry curves of the pristine Fe₂O₃, Au-Fe₂O₃-550, and Au-Fe₂O₃-700 are shown in Fig. 3a. The photoresponse of pristine Fe₂O₃ is very weak, only 4 μA cm⁻² at 1.5 V vs. RHE. By contrast, the Au-Fe₂O₃-550 and Au-Fe₂O₃-700 exhibited remarkable im-

provements, and the corresponding photocurrent density can reach 0.19 and 1.16 mA cm⁻² at 1.5 V vs. RHE, which was nearly 50 and 300 times higher than that of the pristine Fe₂O₃, respectively.

IPCE measurements were tested for pristine Fe₂O₃ and Au-implanted samples under the potential of 1.5 V vs. RHE. IPCE values were calculated from the photocurrent densities obtained under different wavelengths in a range from 300 to 650 nm, and expressed as the following equation [17]:

$$\text{IPCE} = (1240 \times I) / (\lambda \times J_{\text{light}}),$$

where *I* (mA cm⁻²) is the photocurrent density, λ (nm) is the incident wavelength, and J_{light} (mW cm⁻²) is the power density of irradiance at a specific wavelength. As shown in Fig. 3b, the total IPCE value of pristine Fe₂O₃ is lower than 1% across the entire test range (300–650 nm), which is consistent with the negligible photocurrent density shown in Fig. 3a. Significantly, the IPCE is 4.2% for Au-Fe₂O₃-550 and 25.8% for Au-Fe₂O₃-700 at 350 nm. Particularly, the IPCE of Au-Fe₂O₃-700 still maintains more

Figure 4 (a) Nyquist plots of pristine Fe₂O₃, Au-Fe₂O₃-550 and Au-Fe₂O₃-700 at a potential of 1.5 V (vs. RHE) under simulated AM 1.5 G illumination. The inset shows magnified Nyquist plot of Au-Fe₂O₃-700. (b) Charge separation efficiency and (c) charge injection efficiency of pristine Fe₂O₃, Au-Fe₂O₃-550 and Au-Fe₂O₃-700; (d) summary of significant PEC parameters of pristine Fe₂O₃, Au-Fe₂O₃-550, Au-Fe₂O₃-700 samples.

than 10% in the visible light (14.1% at 420 nm).

In addition, we also investigated the effect of Au ion implantation dosage on PEC water splitting performance. As seen in Fig. 3c, the sample with the implantation dosage of 5×10^{16} ions cm⁻² exhibits the best PEC water splitting performance. It is considered that smaller implantation dosage resulted in fewer Au particles and Fe²⁺ species, meanwhile, over-dosage implantation sputtered too much hematite, which led to degradation of overall photoactivity. We also studied the effects of different annealing temperatures on the PEC performance of Au-implanted Fe₂O₃ samples (Fig. S4). Results suggest the lower temperature annealing process (at 350 and 450°C) exhibited poor PEC water splitting performance, because lower temperature annealing cannot well repair the lattice damage caused by Au ion implantation. Finally, we tested *I-t* curves of Au-Fe₂O₃-700 for 8-hour (Fig. 3d), and impressively, the photocurrent density remained stable, indicating the excellent stability of Au-Fe₂O₃-700 sample.

To find out the enhancement mechanism of Au-im-

planted Fe₂O₃, electrochemical impedance spectroscopy (EIS) was tested firstly for pristine Fe₂O₃, Au-Fe₂O₃-550, and Au-Fe₂O₃-700 at the potential 1.5 V vs. RHE (Fig. 4a). The Nyquist diagram of each sample shows an apparent semicircle, which is mainly associated with charge transfer resistance (R_{ct}). R_{ct} values were fitted by a simple Randle circuit model shown in the inset of Fig. 4a. R_{ct} values of Au-Fe₂O₃-550 and Au-Fe₂O₃-700 (Fig. 4d) are much smaller than that of pristine Fe₂O₃, indicating that the Au-implanted samples obtained much better electrical conductivity, which can be resulted from the synergistic effects of Fe²⁺ species and Au particles. To get more deeply insight into the enhancement mechanism, we measured the charge separation and charge injection efficiency using the H₂O₂ as the hole scavenger in the electrolyte [30,48]. The charge separation efficiency was calculated with the following equation:

$$\eta_{\text{charge separation}} = J_{\text{H}_2\text{O}_2} / J_{\text{absorbed}},$$

where $\eta_{\text{charge separation}}$ is the charge separation efficiency of

the photogenerated carriers, $J_{\text{H}_2\text{O}_2}$ is photocurrent density under the 458 nm monochromatic light at 1 mol L^{-1} NaOH+0.5 mol L^{-1} H_2O_2 electrolyte, and J_{absorbed} is the power density of irradiance of 458 nm monochromatic light. The charge injection efficiency was calculated with the following equation:

$$\eta_{\text{charge injection}} = J_{\text{light}} / J_{\text{H}_2\text{O}_2},$$

where $\eta_{\text{charge injection}}$ is the charge separation efficiency of the photogenerated carriers, J_{light} is photocurrent density under the AM 1.5 G illumination at 1 mol L^{-1} NaOH electrolyte, and $J_{\text{H}_2\text{O}_2}$ is photocurrent density under the AM 1.5 G illumination at 1 mol L^{-1} NaOH+0.5 mol L^{-1} H_2O_2 electrolyte [49]. It can be seen in Fig. 4b, the charge separation efficiency of Fe_2O_3 is about 1%, which is consistent with intrinsic properties of hematite as a Mott insulator. By contrast, the charge separation efficiency of Au- Fe_2O_3 -550 and Au- Fe_2O_3 -700 was elevated to be about 6%. Meanwhile, the charge injection efficiency of pristine Fe_2O_3 was lower than 4% (Fig. 4c), while that of Au- Fe_2O_3 -550 was elevated to 25%. Impressively, the charge injection efficiency of Au- Fe_2O_3 -700 was greatly increased to 89%. It should be noted that Au- Fe_2O_3 -550 and Au- Fe_2O_3 -700 have similar charge separation efficiency; however, the charge injection efficiency of Au- Fe_2O_3 -700 is much higher than that of Au- Fe_2O_3 -550. This suggests that tighter contact between hematite and Au particles can greatly promote photogenerated carrier injection process. Based on a series of characterizations and analyses above, we concluded that Fe^{2+} species and tightly contacted Au particles can greatly promote the separation and injection of photogenerated carriers. Therefore, the PEC water splitting performance of Au ion implanted Fe_2O_3 was significantly enhanced compared with pristine Fe_2O_3 .

CONCLUSIONS

In summary, we have employed Au ion implantation and following high-temperature annealing to greatly improve the PEC water splitting performance of hematite. Based on a series of characterizations and analyses, we found that the Fe^{2+} species and tightly attached Au particles can significantly promote the separation and injection of photogenerated carriers. Particularly, the stronger contact between Au particles and hematite, formed at higher temperatures, can tremendously improve the charge injection efficiency to 89% at 1.5 V vs. RHE. Therefore, the photocurrent density of optimized Au-implanted Fe_2O_3 can reach 1.16 mA cm^{-2} , which is significantly enhanced compared with the negligible photoresponse of pristine

Fe_2O_3 ($4 \mu\text{A cm}^{-2}$ at 1.5 V vs. RHE). Meanwhile, Au-implanted Fe_2O_3 photoelectrode exhibited great stability in the 8-hour PEC water splitting test without photocurrent decay. This novel and effective method also has the potential to become a general way to enhance the PEC performance of other PEC materials.

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Conflict of interest The authors declare that they have no conflict of interest.

Supplementary information Experimental details and supporting data are available in the online version of the paper.

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使用离子注入产生金颗粒和 Fe^{2+} 显著增强 $\alpha\text{-Fe}_2\text{O}_3$ 光电化学性能

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摘要 光电化学催化分解水是一种极具发展前景的生产 H_2 和 O_2 的方法. $\alpha\text{-Fe}_2\text{O}_3$ 由于其具有优良的光电化学稳定性、无毒害、地球储量大以及合适的能带宽度 $E_g \sim 2.1$ eV等优点, 被认为是最有潜力的光电催化分解水的材料之一. 然而由于其空穴传输距离短(约2~4 nm)、导电性差、光生载流子复合速度极快等原因, $\alpha\text{-Fe}_2\text{O}_3$ 的光电催化分解水的效率受到了极大限制. 在此, 我们报道了一种新颖并且高效的离子注入Au元素并且退火的方法显著提高了 $\alpha\text{-Fe}_2\text{O}_3$ 光电化学分解水的效率. 根据一系列的表征和分析, 发现 Fe^{2+} 和紧密接触的金颗粒在金注入的 $\alpha\text{-Fe}_2\text{O}_3$ 样品中产生. 因此, 金注入的 $\alpha\text{-Fe}_2\text{O}_3$ 样品的载流子分离效率和注入效率得到了显著提高. 该样品光电流密度在1.5 V vs. RHE偏压下可以达到 1.16 mA cm^{-2} , 相对原始样品光电流密度提升接近300倍($4 \mu\text{A cm}^{-2}$). 此外, 金注入的 $\alpha\text{-Fe}_2\text{O}_3$ 样品在8 h的光电催化分解水的测试中没有出现光电流衰减的现象, 表现了良好的稳定性.