Physical and photo-electrochemical properties of the spinel SrFe$_2$O$_4$: application to hydrogen production under visible light

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ABSTRACT

SrFe$_2$O$_4$ prepared by sol–gel method after annealing at 800 °C crystallizes in a normal spinel structure. The structural, morphological, magnetic, optical, transport, and photo-electrochemical properties were systematically investigated. The sol–gel permits to have nanocrystallites with an average size of $\sim$ 30 nm. The UV–Visible diffuse reflectance analysis gives a direct transition of 1.80 eV, resulting from the Fe^{3+}: *3d* orbital splitting in octahedral site. Such degeneracy lifting into (t$_{2g}$–e$_g$) levels is properly matched to the sun spectrum. The capacitance–potential (C^{-2} − E) characteristic of SrFe$_2$O$_4$ plotted in basic electrolyte (KOH 0.1 M) exhibits *p*-type comportment with a flat band potential of (E$_{fb}$) of 0.01 V$_{SCE}$, a holes density (N$_A$) of 1.4×10^{15} cm^{-3}, and an extended space charge region of 0.9 µm. The electrochemical impedance spectroscopy exhibits a semicircle characteristic of the charge transfer whose diameter decreases under irradiation, thus supporting the semiconducting character of SrFe$_2$O$_4$. The electrons in the conduction band (− 1.70 V) have a high reducing ability and cathodically positioned with respect to the H$_2$O/H$_2$ level, thus producing H$_2$ evolution under visible light illumination with a concomitant oxidation of SO$_3^{2-}$/S$_2$O$_6^{2-}$. The best activity occurs at pH $\sim$ 11 with H$_2$ evolution rate of 35 µmol mn^{-1} g^{-1} and a quantum yield of 1.8% under visible light (29 mW cm^{-2}).

1 Introduction

The fossil energy reserves will soon start declining and the photo-electrochemical (PEC) conversion of visible light to electrical and/or chemical energy continues to attract a much attention in the scientific community [1–3]. Algeria has a high solar potential with an annual insulation of $\sim$ 3200 h and an average solar constant exceeding 1200 W m^{-2} (South). However, the intermittence of this energy requires its storage to be released on demand. In this respect, hydrogen with environmentally friendly characteristic is suitable for

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long-term storage with a capacity of 28,540 cal g^{-1}. It can be produced photo-electrochemically and considerable works have been focused on ferromagnetic materials active under UV–Visible light, and the *3d* metal-based oxides remain privileged because of their chemical stability, high saturation magnetization, thermal properties, and facile synthesis [4–9] compared to sulfide. However, many of them suffer from limitations including a wide gap (E_g), due to the crystalline structure with a valence band (VB) made up of O^{2-}: $2p$ orbital, while the conduction band (CB) derives mostly from metal character [10]. This drawback can be overcome by raising the energy of VB and this occurs by introduction of cationic orbital, which not only decreases the gap but maintains a high reducing ability of CB. In this category, the spinel magnetic nanomaterials MFe_2O_4 (M=Sr, Te, Ni, Co, etc.) continue to attract a growing interest in electronic, optic, magnetic resonance, biosensors, and photocatalysis [11–20] due to their magnetism and absorption over the visible region. In addition, they have pH-independent double layer through which the potential of $H2O/H2$ couple, which varies by ~ 60 mV pH^{-1}, can be judiciously located. This constitutes a further advantage to have an optimal band bending (~ 0.4 V) at the semiconductor/electrolyte junction [21].

On the other hand, the preparation of nanocrystallites is attractive for small polaron oxides with a low carriers' mobility [22], and the spinels were the object of nano-sized effect inquiry [23, 24]. Hence, the conversion of the incident light to electrical current or chemical energy increases with decreasing the crystallite size till it becomes comparable with both the diffusion length of the minority carriers and the light preparation (α^{-1}_λ), where α_λ is the absorption coefficient which depends on the wavelength (λ) [25]. In such a case, the electrons have a high probability to reach the liquid phase to reduce water into hydrogen [26, 27].

The main goal in photocatalysis is to produce large surface areas with crystallites size as small as possible and the sol–gel route seems appropriate in such a case. Our approach is then to prepare SrFe2O4 with nano-morphology of the kind obtained with the spinel NiFe2O4 [28]. The choice of SrFe2O4 for the hydrogen production is motivated by the friendly environmental characteristic, chemical inertness in aqueous medium, and absorption over the visible region. To our knowledge, the photo-electrochemical characterization of SrFe2O4 is missing, and the photocatalytic properties

have been little investigated. The main purpose of this work was to describe the synthesis of SrFe2O4, to study its optical, magnetic, morphological, and photo-electrochemical properties in order to be applied for the hydrogen production upon visible light irradiation. Hydrogen is reported because of its chemical stability, low cost, and optimal gap. The loss by recombination is minimized by using a hole scavenger, and SO_3^{2-} is appropriate in our case.

2 Experimental

SrFe2O4 was synthesized by sol–gel method from Sr(NO3)2 (Merck, 99%) and Fe(NO3)3, 9H2O (Flucka, > 98%), dehydrated in a dessicator under static vacuum for several days. The stoichiometric amounts {molar ratio Sr/Fe:1/2) were dissolved in distilled water containing agar-agar (1 g L^{-1}); the solution was heated at 70 °C (3 h) and 100 °C (4 h) until total evaporation. Then, the powder was crushed in an agate mortar and fired at 800 °C with intermediate regrinding. The phase has been confirmed by X-ray diffraction (XRD) using a Phillips diffractometer with Cu Kα radiation (λ = 0.15418 nm) in the 2θ range (20°–80°).

The FTIR spectrum was performed and plotted with a Bruker Alpha (P1000) spectrometer in the range (400–4000 cm^{-1}). The X-ray photoelectron spectroscopy (XPS) was performed with Source Gun AA < Ê = X-Ray 000 350 μm—FG ON (350 μm). The calibration was made by considering the C1s peak (289.4 eV). The SEM images were visualized with a Jeol JSM-7610 F equipped with a Noran EDS detector. The N_2 adsorption–desorption isotherms were obtained by BET surface area analyzer (ASAP 2010 V5.02). The magnetic measurement was carried out at room temperature by using a Vibrating Sample Magnetometer (Microsense easy VSM software) in a magnetic field range ± 24,000 Oe which gives the variation among the applied field H and magnetization M.

The band gap (E_g) of SrFe2O4 was determined from the diffuse reflectance using a UV–Visible spectrophotometer (Model: Specord 200 Plus) and polytetrafluoroethylene as reference. The pellets, sintered at 850 °C, were electrically contacted to a copper wire with silver paint; the electrical conductivity was measured by the two probe method using GW Instek equipment (GDM 8255A). The data were accurate

to $\pm\,5\;\Omega$ cm, and the temperature was controlled with a Cr–Al thermocouple.

The photo-electrochemical study was done in a standard Pyrex cell; the pellets were encapsulated in glass tubes with insulating araldite, leaving a geometric surface area of 1.12 cm^2. A PGZ301 Potentiostat was employed for the acquisition of electrochemical data; a saturated calomel electrode (SCE) and Pt foil were used as reference and auxiliary electrodes, respectively. The electrochemical impedance spectroscopy (EIS) was performed over the frequency range (1 mHz–100 kHz), while the Mott–Schottky characteristic was plotted at a frequency of 10 kHz. All experiments were initiated after stabilization of the open circuit potential (OCP).

The photocatalytic tests were carried in a water-cooled Pyrex reactor housing three tungsten lamps (3 × 200 W); the flux intensity (29 mW cm^{-2}) was measured with a digital light meter (Testo 545). The temperature was maintained at 50 ($\pm\,1$ °C) thanks to a thermo-stated bath. SrFe2O4 powder (200 mg) was immersed in 200 mL of SO_3^{2-} (0.025 M) solution, and the pH was adjusted by the addition of KOH. The powder was uniformly dispersed under moderate agitation at 210 rpm to occupy the whole reaction space and to preclude the vortex phenomenon. The solution was bubbled by N_2 gas at a purging rate of 10 mL mn^{-1}; after 35 min, the light was switched on. Hydrogen was qualitatively identified by gas chromatography (Agilent Technology 7890A); because of its low solubility, the amount was quantified volumetrically in a graduated burette by water displacement due to the pressure produced inside the reactor.

3 Results and discussion

The synthesis of oxides by solid state reaction requires high temperatures, leading to irregular and large crystallites with low active surface areas. By contrast, the sol–gel route produces more or less homogenous powder with a narrow size distribution [29]. The XRD pattern of SrFe2O4 (Fig. 1) is characteristic of a single phase crystallizing in a spinel structure; the peaks are indexed with a cubic symmetry in agreement with the JCPDS Card N° 001-1027. The lattice constant (a) and spacing between crystal planes (d_{hkl}) are linked by the relation [16, 30]:
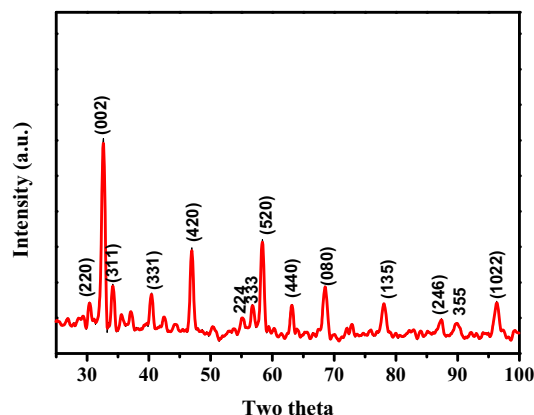

Fig. 1 X-ray diffraction pattern of SrFe$_2$O$_4$ prepared by sol–gel route and calcined at 800 °C

$$a = d_{hkl}\sqrt[2]{h^2 + k^2 + l^2} \qquad (1)$$

We do not detect any peak due to secondary phase like the deficient perovskite Sr2Fe2O5 [31] or SrO which converts into Sr(OH)2 when exposed to free atmosphere. The sharp peaks indicate small crystallites size (D = 31 nm) (β in rd., = $K\lambda/\beta\cos\theta$), where K (= 0.94) is the shape factor and β (rd.) is the broadening at half maximum. The dislocation density (δ) was calculated with the help of the value of crystallite size using the following relations: [32]

$$\delta = \frac{1}{D^2} \qquad (2)$$

$$V = a^3 (\text{Å}^3) \qquad (3)$$

An active surface area of SrFe2O4 was calculated from the relation (= $6/\rho_{XRD}D$), where ρ_{XRD} is the theoretical density (5.36 g cm^3). The lattice constant, unit cell volume, crystallite size, and dislocation density of the spinel oxide are given in Table 1.

The FTIR spectroscopy is a useful technique for identifying the chemical absorption. The two broad bands in the spectrum are assigned to metal–oxygen of the ferrite spinel (Fig. 2). The highest one, v1 in the range (800–600 cm^{-1}), corresponds to stretching vibrations of the metal in tetrahedral site (T_d), Mtetra

Table 1 Lattice constant (a), unit cell volume (V), crystallite size (D), and the dislocation density of SrFe$_2$O$_4$ nanoparticle

Parameters	a (Å)	V (Å^3)	D (nm)	δv10^{-3} (lines/nm^2)
SrFe$_2$O$_4$	5.50	166.375	30.89	1.048

MO, while the lowest $v2$ band in the region (550–400 cm^{-1}) is attributed to octahedral—metal stretching (O_h), Mocta MO [33–36]. The SEM micrographs of $SrFe_2O_4$ (Fig. 3) show give grains morphology. Some grains are necked in shape, due to the diffusion among the particles during sintering. This means that the smaller particles join together to form the larger particles[37]. Images show an intense and irregular dispersion of conglomerates without specific morphology [38]. Agglomeration occurs between the particles, due to the dipole–dipole interaction among the particles [39], and the elemental composition (Fig. 3) gives 38.56% of Sr, 32.18% of O, and 24.95% of Fe.

The XPS analysis was used to determine the composition and surface valence states (Fig. 4), The characteristic lines of O, Sr, and Fe of the spinel are observed, and the carbon peak C 1 s (289.23 eV) is due to the grid used for analysis and/or CO_2 adsorption. The analysis of the curves fitting revealed that Sr^{2+} and Fe^{3+} species are located in different sites (tetrahedral-A and octahedral-B). The deconvoluted spectrum of O 1 s orbital (Fig. 4a) shows one typical peak due to chemical state of oxygen (531.5 eV) in Sr–O–Fe. Figure 4b displays the spectrum of Sr 3d orbital with two peaks at 135.28 and 133.4 eV assigned to Sr 3d3/2 and Sr 3d5/2 orbitals, respectively. Figure 4c illustrates the spectrum of Fe 2p orbital, where the peaks 724.28, 710.78, and 718.68 eV correspond to Fe 2p1/2 and Fe 2p3/2 orbitals respectively [47]. The peaks at 710 eV and 718.68 eV are assigned to the presence of Fe^{3+} located respectively in the A- and B-sites, indicating that Fe^{3+}
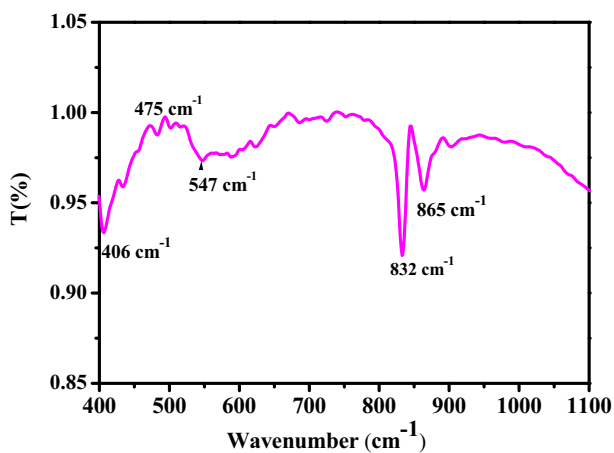
favors rather octahedral coordination in the spinel structure.

The N_2 adsorption–desorption isotherm of $SrFe_2O_4$ (Fig. 5) gives a specific surface area of 26 $m^2\ g^{-1}$.

The magnetic properties of $SrFe_2O_4$, such as saturation magnetization (M_s), residual magnetization (M_r), and coercive field (H_c), as well as the squareness ratio M_r/M_s, were measured at room temperature in a magnetic field ranging from − 24,000 to 24,000 Oe (Fig. 6 and Table 2). An hysteresis loop was observed from the magnetization curve M(H), characteristic of a hard ferrite with ferromagnetic behavior and a Curie temperature above 300 K, due to the magnetization M_r (6.045 emu/ g) when the field (H) is zero. The significant field H_c (3892 Oe) makes this spinel ferrite resistant to demagnetization [40, 41]. Our sample with a squareness ratio of 0.47 (< 0.5) has a single domain structure, whereas materials with a ratio greater than 0.5 have a multi-domain structure [42]. So, we conclude that the prepared ferrite exhibits better magnetic properties, a desired property in photocatalysis.

The optical gap (E_g), vital in the photo-electrochemical conversion, quantifies the solar flux converted into useful energies. It is determined from the diffuse reflectance (R) by using the relation:

$$(\alpha_\lambda h v)^m = (E_g - h v) \tag{4}$$

The exponent m is equal to 0.5 or 2, respectively, for indirect and direct transitions. The E_g value (1.85 eV) is obtained by extrapolating the line $(\alpha\lambda h v)^2$ to the energy-axis (Fig. 7), and the transition is directly allowed indicating that the top of the valence band (VB) coincides and the bottom of the conduction band (CB) is with no phonon assistance. The E_g value is close to that obtained elsewhere [43]; $\alpha\lambda$ (cm^{-1}) is the absorption coefficient and its inverse represents the light penetration of the monochromatic light (λ). The gap (E_g) results from the octahedral crystal field splitting of Fe^{3+}: $3d$ orbital into three lower energy levels $t2g$ and two upper levels eg. It describes the lifting of orbital degeneracy in the Fe^{3+} complexes due to the presence of oxygen octahedra and the strength of the Fe–O bond.

The semi-conductivity is a required property in photocatalysis and depends on the extent of deviation from the stoichiometry. The Hall effect cannot be measured, indicating a resistive oxide ($\sigma_{300K} < 10^{-6}$ $\Omega^{-1}\ cm^{-1}$) with a low holes density (see below.) The
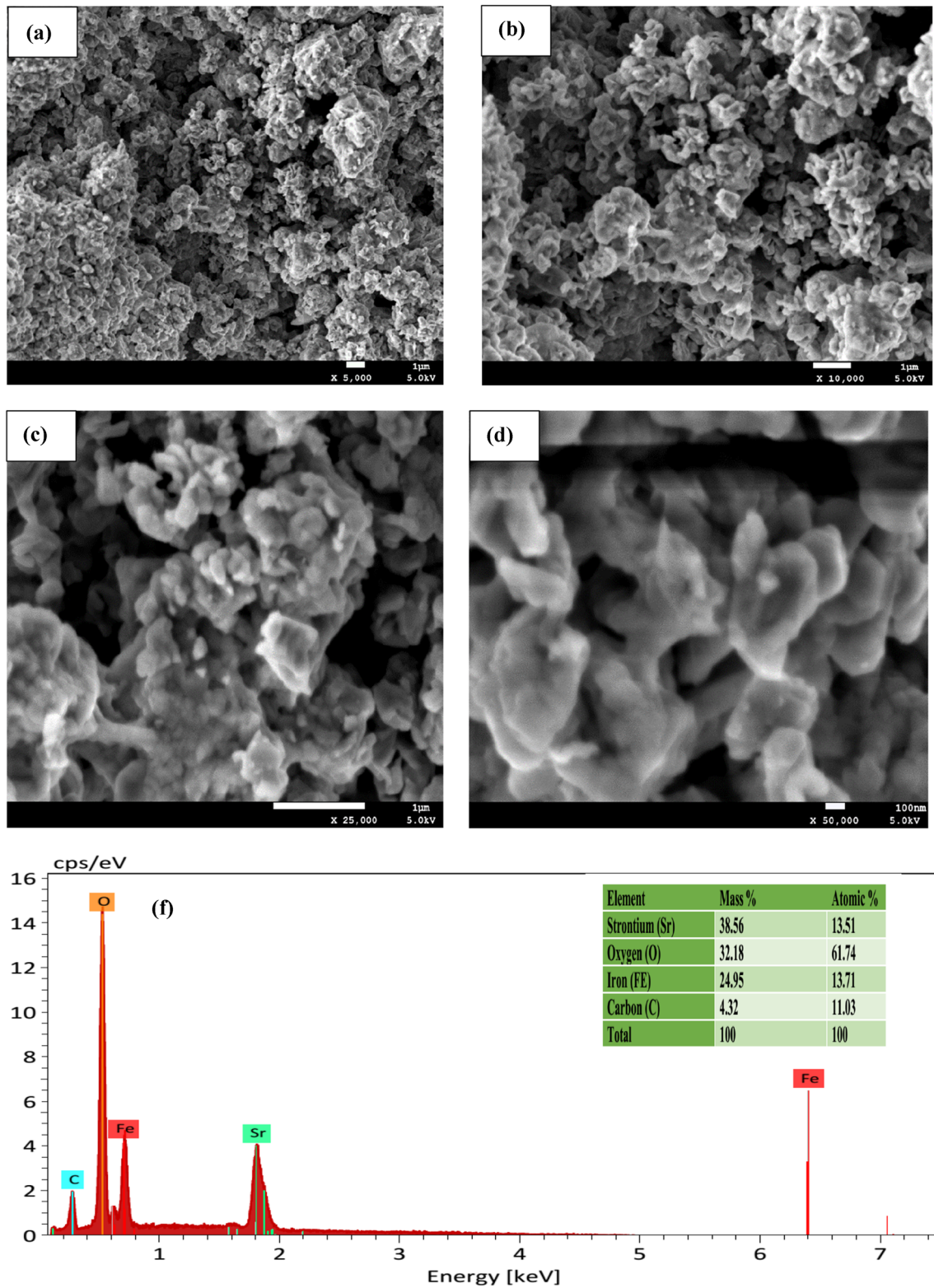

Fig. 2 FTIR spectrum of $SrFe_2O_4$ prepared by sol–gel route

Fig. 3 SEM images showing the morphology of $SrFe_2O_4$ at different magnifications. **a** ×5000, **b** ×10,000, **c** ×25,000, **d** ×50,000 ,and **f** EDX composition of $SrFe_2O_4$

Fig. 4 Survey XPS spectra for $SrFe_2O_4$, resolved core level spectra. O (1 s) (**a**), Sr (3d) (**b**) and Fe (2p) (**c**)

electrical conductivity (σ) follows an exponential law $\{\sigma = \sigma o \exp \{- E_a/kT)\}$, characteristic of a classical semiconductor; the activation energy (E_a) was deduced from the slope $d\log\sigma/dT^{-1}$ (Fig. 8.). This seems to be not an intrinsic property but due to Fe^{3+} ions in interstitial site, dominated by small polarons lattice, thermally activated.

The chemical inertness of the material is also crucial for the photocatalytic applications. By immersion for 1 week in the working solution (pH 12.5), SrFe2O4 shows no deterioration; the reaction of Fe^{3+}, after acidification, by SCN^- was negative, and no red coloration due to the complex $Fe(SCN)^{2+}$ was observed.

The intensity–potential $J(E)$ profile of SrFe2O4 plotted in KOH electrolyte exhibits a plateau region over a large potential range, a behavior similar to a chemical diode, indicating a good electrochemical stability with a tunneling effect at large anodic polarization. The photocurrent (J_{ph}) corresponding to the change in the current induced under visible irradiation, J_{ph}, augments in the cathodic side, thus, implying p-type conductivity which becomes pronounced below $- 0.4$ V, and the onset photocurrent potential (E_{on}) is taken as the potential above which no photocurrent flows (Fig. 9).

The ability of a semiconductor to drive the H_2 evolution is governed by the position of its conduction band (CB), which must be more negative than the H2O/H2 level. In this regard, the

Fig. 5 N_2 adsorption–desorption isotherms of the spinel $SrFe_2O_4$ at -196 K

Fig. 7 Direct and indirect optical transitions of $SrFe_2O_4$ prepared by sol–gel route

Fig. 6 Magnetic hysteresis loop for $SrFe_2O_4$ prepared by sol–gel method
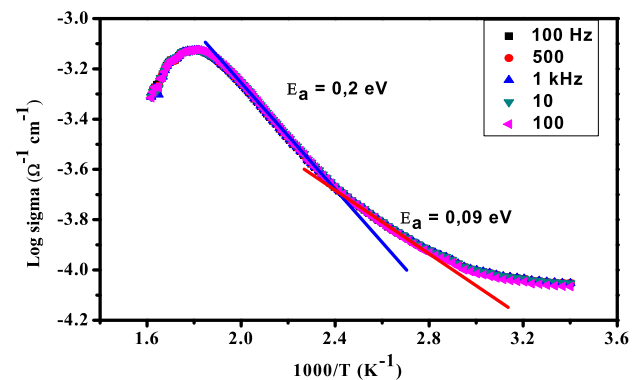
Fig. 8 Logarithm of the electrical conductivity of $SrFe_2O_4$ vs. reciprocal temperature

Table 2 Magnetic parameters for $SrFe_2O_4$ spinel ferrite

Sample	Saturation magnetization M_s (emu/g)	Remanent magnetization M_r (emu/g)	Coercivity H_c	M_r/M_s
$SrFe_2O_4$	12.84	6.045	3892.62	0.47

capacitance−potential ($C^{-2} - E$) plot is used for a reliable determination of CB:

$$C^{-2} = \{2/\varepsilon\varepsilon_0 N_A\}\{E - E_{fb}\} \tag{5}$$

All symbols have their usual significations. The flat band potential ($E_{fb} = 0.01$ V) is simply deduced by extrapolating the linear plot to infinite capacitance ($C^{-2} = 0$) (Fig. 10), and is equivalent to the built-in potential in the solid state. The negative slope confirms the p-type conductivity where the majority carriers are holes. The semi-logarithmic (Fig. 11) confirms the electrochemical stability of the

spinel. The energy of CB ($= e \times E_{fb} + E_a - E_g$) is positioned at 3.05 ± 0.10 V below vacuum [44] (Fig. 12). It corresponds to a potential of -1.70 V, more cathodic than that of hydrogen and should trigger the H_2 evolution under visible illumination. The valence band (VB: 4.85 eV/0.1 V) is simply deduced from the relation:

$$E_{VB} = E_{CB} - E_g \tag{6}$$

EIS analysis quantifies the different contributions of the solid/liquid junction and provides information on the electron transfer mechanism. It is a non-stationary
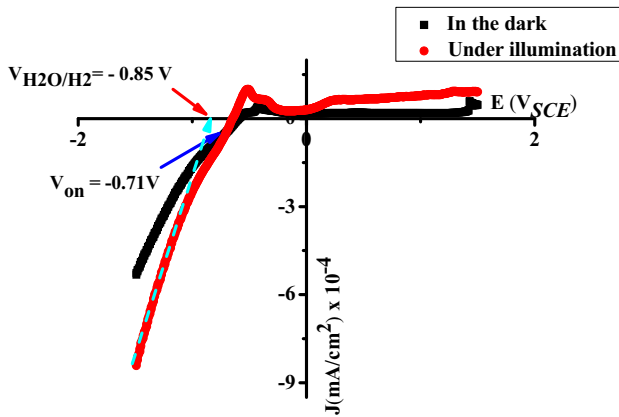
Fig. 9 The $J(E)$ plots of SrFe$_2$O$_4$ electrode in KOH solution (0.5 M) under N$_2$-atmosphere in the dark and under visible irradiation. Scan rate 10 mV/s
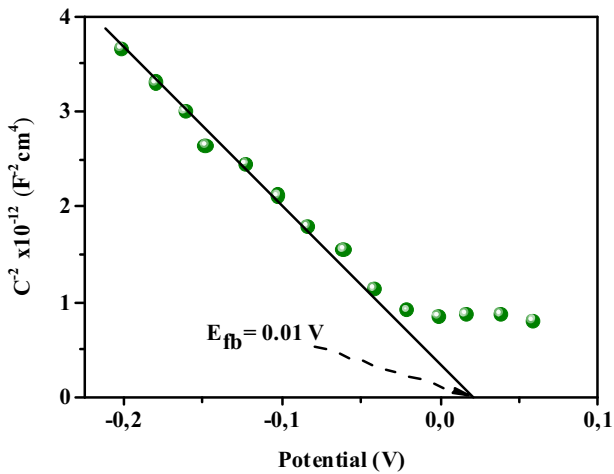

Fig. 10 The Mott−Schottky characteristic of SrFe$_2$O$_4$ plotted in KOH solution at a frequency of 10 kHz
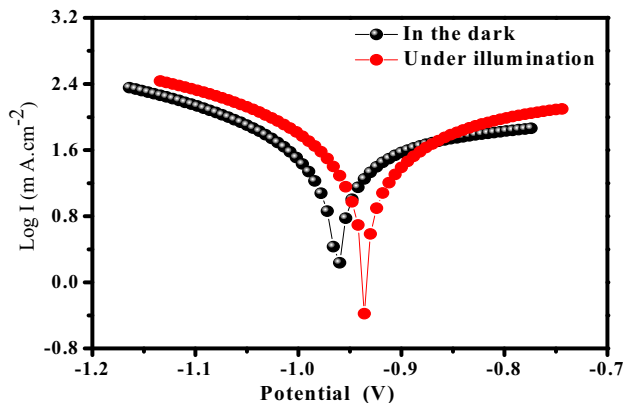

Fig. 11 Semi logarithmic plots of SrFe$_2$O$_4$ in KOH (10^{-2} M) solution under N$_2$ bubbling; scan rate 10 mV/s

technique and the excitation with small amplitude does not modify the system, thus permitting repeated tests at the free potential (Fig. 12). The occurrence of two loops in the EIS plot of SrFe2O4 is due to the bulk and grains boundaries. As expected, the diameter of the first semicircle decreases under illumination (Fig. 13), thus corroborating the semiconducting behavior. The EIS diagram does not show a straight line at low frequencies, indicating the absence of Warburg impedance. Such observation agrees with the existence of a plateau region in the $J(E)$ characteristics. The center of the semicircle is located below the real axis, due to a deviation from a pure capacitive behavior with the existence of a constant phase element (CPE). An electrical equivalent circuit is suggested by fitting the data with the Z-View software.

4 Photocatalysis

The oxide is not deliberately doped and the low holes density extends the space charge region up to ∼ 0.9 μm, allowing the participation of the most electron/hole (e$^-$/h$^+$) pairs in the photoactivity. The distance traveled by the electrons to reach the interface decreases, and these electrons are then captured by the water adsorbed on the surface inside the pores.

As mentioned above, SrFe2O4 is a small polaron semiconductor with a low carrier mobility ($\mu_h \sim 10^{-6}$ cm^2 V^{-1} s^{-1}), the latter is calculated from the relation ($\sigma = \mu e N_A$). Therefore, the adopted strategy was to reduce the crystallite size below diffusion length, and the advantage of sol–gel is to produce small crystallites with increased specific surface. Nanoparticles with sizes (D) in the range (30–50 nm) give enhanced active
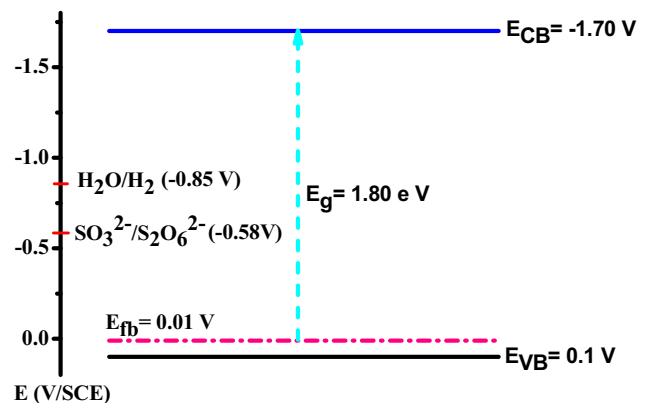

Fig. 12 Energetic diagram of the junction SrFe$_2$O$_4$/KOH electrolyte, given in the electrochemical scale at pH 7
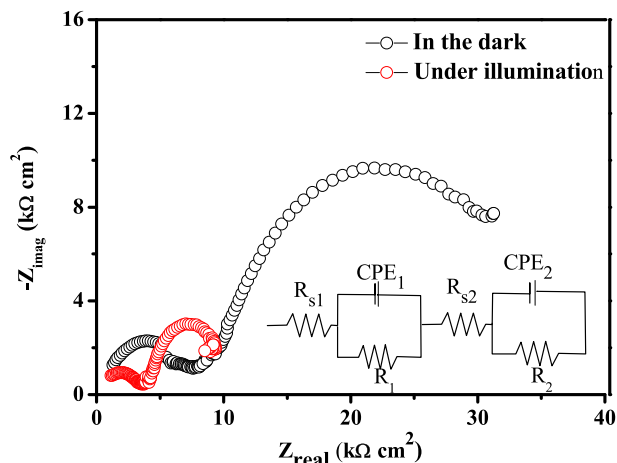
Fig. 13 The complex impedance spectroscopy of SrFe$_2$O$_4$ in KOH solution plotted in the dark and under illumination. Inset: the equivalent electrical circuit

Fig. 14 Volume of evolved H$_2$ on SrFe$_2$O$_4$ in alkaline medium (KOH, 10^{-2} M + Na$_2$SO$_3$, 0.025 M)

surface area with more photocatalytic sites. A specific surface area of ~ 26 m^2 g^{-1} was evaluated from the BET analysis. The electrochemical characterization revealed chemical stability in KOH electrolyte under irradiation. The excited electrons have a cathodic potential, sufficient to convert water into hydrogen.

Hydrogen is a nonpolluting fuel with no greenhouse gases emission and could bring a partial solution for the clean energy supply and environmental protection [45, 46]. The maximum photovoltage produced by a semiconductor under irradiation cannot exceed E_g/e. Accordingly, to split water into oxygen and hydrogen, a gap greater than 2.2 eV is required because of the high O2-over-voltage [48]. So, O2 cannot be evolved through by a valence band process and a reducing agent must be used to capture the photoholes; this improves the charges separation and protects the oxide against the photo-oxidation [49]. Figure 12 depicts a possible photocatalytic reaction mechanism of SrFe$_2$O$_4$. The electrons are excited to the conduction band, leaving holes on the valence band (8). The photogenerated electrons focalized to H$_2$O molecules to be reduced into H$_2$, while the holes react on the surface with SO$_3^{2-}$. On the other side, the pH has a great influence in photoelectrochemistry. The results (Fig. 14) show that SrFe$_2$O$_4$ is active at various pHs, leading to different performances. The best activity is obtained at pH ~ 11, followed by pH 7 and 3 because the potential $E(H_2)$ moves toward the cathodic direction, producing an optimal interfacial band bending at pH ~ 11 with a complete separation of (e$^-$/h$^+$) pairs. The H$_2$
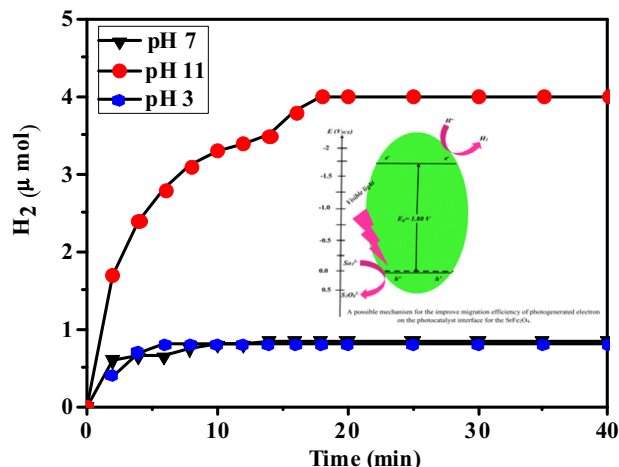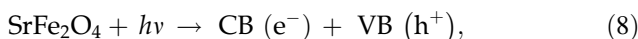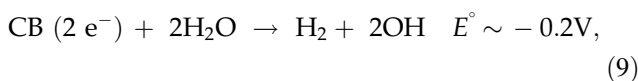
formation needs two electrons, and the conversion efficiency is given by the relation:

$$\eta = 2 \times \{\text{number of H}_2 \text{ mol s}^{-1}\}/\text{photons flux s}^1\}$$ (7)

Water is reduced into hydrogen, while SO$_3^{2-}$ is concomitantly oxidized according to the following sequences:

$$\text{SrFe}_2\text{O}_4 + h\nu \rightarrow \text{CB (e}^-) + \text{VB (h}^+),$$ (8)

Cathodic pole

$$\text{CB (2 e}^-) + 2\text{H}_2\text{O} \rightarrow \text{H}_2 + 2\text{OH} \quad E^{\circ} \sim -0.2\text{V},$$ (9)

Anodic pole

$$2\,\text{SO}_3^{2-} + 2\,\text{h}^+ \rightarrow \text{S}_2\text{O}_6^{2-},$$ (10)

$$\text{SO}_3^{2-} + \text{H}_2\text{O} + 2\,\text{h}^+ \rightarrow \text{SO}_4^{2-} + 2\,\text{H}^+,$$ (11)

$$2\,\text{SO}_3^{2-} + 3\,\text{H}_2\text{O} + 4\,\text{e}^- \rightarrow \text{S}_2\text{O}_3^{2-} + 6\,\text{OH}^-.$$ (12)
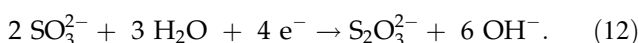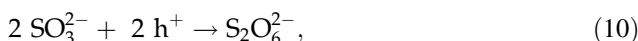
The photocatalytic hydrogen formation occurs in ~ 20 min above which a net tendency to saturation was observed. This indicates that the reaction (11) is disfavored, otherwise the saturation should not be observed since the sulfate with a redox potential of ~ 2 V is stable and does not compete with photoelectrons. Therefore, one can conclude that the deactivation of the catalyst by H2-adsorption is due to competitive reaction (12) where the thiosulfate S$_2$O$_3^{2-}$ consumes the photo-electrons. The saturation of catalytic sites also accounts for the regression of the

photoactivity. More interestingly, the initial activity of the catalyst powder is completely restored during the second cycle.

Our research suggests that pursuing the synthesis of spinel AFe_2O_4 by Sol–Gel method, A denotes a alkaline earth metals. This is the goal to study the impact on the physico-chemical properties on the H_2 photo-production.

5 Conclusion

The spinel $SrFe_2O_4$ was synthetized by sol–gel route with an average crystallite size of 40 nm. It is an attractive photocatalyst, due to its chemical stability, low cost, and optical gap of ~ 1.8 eV close to the optimal conversion value. The electronic bands are made up of $3d$: orbital with a high reducing ability and appropriately positioned with respect to H_2 level. The formation of cubic phase was confirmed by XRD analysis. The irregular and intense morphology of the spinel was observed by the SEM images. The VSM reveals a hard ferrite with a ferromagnetic behavior due to the presence of the magnetization M_r (6.045 emu g^{-1}) for a zero applied magnetic field. The XPS analysis revealed that Sr^{2+} and Fe^{3+} are located respectively in four- and six-fold coordination. The d-d optical transition comes from the crystal field splitting of Fe^{3+}: $3d$ in octahedral site. The thermal dependence of the electrical conductivity showed a semiconductor behavior with an activation energy of 0.09 eV. The capacitance measurement gave a flat band potential of 0.01 V_{SCE} and a hole density of 1.4×10^{15} cm^{-3}. The electrochemical characterization revealed chemical stability and the potentiality of $SrFe_2O_4$ in photocatalysis. Indeed, the spinel was tested for the hydrogen formation under illumination and the best activity occurs at pH ~ 11 with H_2 evolution rate of 35 μmol mn^{-1} g^{-1} and a quantum yield of 1.8%. Therefore, the oxidation of sulfite permits to protect the spinel against photo-corrosion and to improve the charges separation. The saturation over time course evolution is due to the competition reduction of thiosulfate $S_2O_3^{2-}$ and occupation of photo-electrochemical sites by adsorbed hydrogen.

Acknowledgements

Author contributions

NH supervised the work, NH and MT discussed the results and wrote the manuscript. SA and NH performed the experiments, GR did the application part. NH and MT and YB discussed the results.

Data availability

All data generated or analyzed during this study are included in this published article.

Declarations

Conflict of interest All authors declare that they have no financial or non-financial interest in this manuscript.

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