Pr and Ti co-doped Strontium Ferrite as a Novel Hydrogen Electrode for Solid Oxide Electrolysis Cell

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ABSTRACT

Pr and Ti co-doped strontium ferrite oxide $\text{Pr}_{0.3}\text{Sr}_{0.7}\text{Ti}_{0.3}\text{Fe}_{0.7}\text{O}_{3-\delta}$ (PSTF) has been examined as a hydrogen electrode for solid oxide electrolysis cell (SOEC). X-ray diffraction analysis shows that the PSTF material maintains phase stability during 20 hours of treatment under 5% H_2/N_2 conditions. An SOEC with a configuration of PSTF||SDC|YSZ||LSM-YSZ operates under various H_2O concentrations and current densities. As can be observed from the AC impedance spectra of the PSTF electrode, $\text{H}_2\text{O}/\text{H}_2$ adsorption desorption or surface diffusion process is the main rate-limiting step for steam electrolysis reaction. The low-frequency arc R_L obviously depends on the H_2O concentration and the electrolysis current density. Steam starvation in hydrogen electrode occurs at low H_2O concentration and large current density. A maximum current density of 302 mA cm^{-2} is obtained at an electrolysis voltage of 1.46 V in $\text{Ar}/\text{H}_2/60\%\text{H}_2\text{O}$ at 800 °C. The corresponding polarization resistance of PSTF electrode is as small as $0.25 \text{ } \Omega \text{ cm}^2$. This study demonstrates that

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$\text{Pr}_{0.3}\text{Sr}_{0.7}\text{Ti}_{0.3}\text{Fe}_{0.7}\text{O}_{3-\delta}$ is a promising hydrogen electrode material of SOEC for H_2O electrolysis.

Keywords: Solid oxide electrolysis cell; $\text{Pr}_{0.3}\text{Sr}_{0.7}\text{Ti}_{0.3}\text{Fe}_{0.7}\text{O}_{3-\delta}$; Hydrogen electrode; Steam electrolysis

1. Introduction

Solid oxide electrolysis cell (SOEC), which operates reversely as the solid oxide fuel cell (SOFC), has attracted more and more attention because it can directly and efficiently convert renewable electrical energy into chemical fuel energy [1-4]. SOEC is commonly used in hydrogen production from H_2O electrolysis and $\text{CO}_2\text{-H}_2\text{O}$ co-electrolysis. For H_2O electrolysis, when voltage is exerted on the SOEC, water molecules are reduced into hydrogen and oxygen ions at the hydrogen electrode surface. Oxygen ions then pass through the dense electrolyte and are oxidized to oxygen at the oxygen electrode side [1, 5]. The reaction of SOEC can be written as:

Due to the similarity, the anode/cathode of SOFC can be used as cathode/anode for SOEC. The conventional anode of SOFC, Ni-YSZ, has been widely used as the hydrogen electrode of SOEC for high temperature steam electrolysis and exhibits outstanding performance [6, 7]. However, a high concentration of H_2 must be fed to Ni-YSZ hydrogen electrode to protect Ni against oxidation. In addition, Ni-YSZ electrode shows poor redox stability as the agglomeration of Ni particles during prolonged operation at elevated temperature [8-10]. Therefore, active and redox-stable

perovskite oxides have been investigated as the hydrogen electrode materials of SOEC. In recent years, $\text{La}_{1-x}\text{Sr}_x\text{Fe}_{1-y}\text{Ti}_y\text{O}_{3-\delta}$ ($0.2 < x < 0.8$, $0.2 < y < 0.5$) were investigated to determine their suitability as oxygen membrane materials [11]. R. Martínez-Coronado *et al.* [12] demonstrated that oxygen-stoichiometric $\text{La}_{0.5}\text{Sr}_{0.5}\text{Fe}_{0.5}\text{Ti}_{0.5}\text{O}_3$ perovskite and oxygen-deficient $\text{La}_{0.5}\text{Sr}_{0.5}\text{Fe}_{0.5}\text{Ti}_{0.5}\text{O}_{2.75}$ composition could be considered as alternative hydrogen electrodes and oxygen electrodes for SOFCs. Cao *et al.* recently proposes a hydrogen electrode material of $\text{La}_{0.3}\text{Sr}_{0.7}\text{Ti}_{0.3}\text{Fe}_{0.7}\text{O}_{3-\delta}$, which shows a good redox stability and durability in pure CO_2 and excellent electrocatalytic activity for H_2 electrochemical combustion and CO_2 electrolysis [13, 14]. In fact, $\text{SrFeO}_{3-\delta}$ -based perovskites have been studied for more than 10 years. However, pure $\text{SrFeO}_{3-\delta}$ is inadequate as hydrogen electrode material of SOFC or SOEC due to its low redox stability (Fe^{4+} to Fe^{3+}) [15, 16]. A-site and/or B-site doping is reported to significantly affect the lattice structure and physical properties of ABO_3 perovskite oxide. It was reported that the presence of $\text{Ti}^{3+}/\text{Ti}^{4+}$ ions in the B-site stabilized the neighboring oxygen octahedral (BO_6), leading to enhanced structural stability and tolerance towards chemical reduction of the strontium ferrite oxides [17-19]. However, the conductivity and electrochemical performance of the $\text{SrFe}_{1-x}\text{Ti}_x\text{O}_{3-\delta}$ decrease and thermal expansion coefficient increases with increasing Ti content [17, 19]. Yaremchenko *et al.* [20, 21] reported that Pr at the A-site could remarkably affect the oxygen non-stoichiometry and conductivity of doped $\text{Sr}_{1-x}\text{Pr}_x\text{TiO}_{3\pm\delta}$. Ren *et al.* [22] observed that the ionic conductivity of $\text{Pr}_{0.8}\text{Sr}_{0.2}\text{FeO}_{3-\delta}$ was more than one order of magnitude higher than that of $\text{La}_{0.8}\text{Sr}_{0.2}\text{FeO}_{3-\delta}$. And as cathode materials for SOFC, $\text{Pr}_{0.8}\text{Sr}_{0.2}\text{FeO}_{3-\delta}$ as well as $\text{La}_{0.8}\text{Sr}_{0.2}\text{FeO}_{3-\delta}$ exhibits identical impedance.

Inspired by the results above, in this work we co-dope Pr and Ti to strontium

ferrite in order to improve the phase stability and the electrochemical activity. $\text{Pr}_{0.3}\text{Sr}_{0.7}\text{Ti}_{0.3}\text{Fe}_{0.7}\text{O}_{3-\delta}$ as a hydrogen electrode material is examined in various electrolyzing conditions. The performance and stability of this material is characterized, the rate-limiting step is identified and the underlying cause is discussed.

2. Experimental

$\text{Pr}_{0.3}\text{Sr}_{0.7}\text{Ti}_{0.3}\text{Fe}_{0.7}\text{O}_{3-\delta}$ (PSTF) powders were synthesized using a solid state reaction method. Pr_6O_{11} (98.0%, Shanghai YUELONG New Materials Co. Ltd., China), SrCO_3 (99.5%, Sinopharm Chemical Reagent Co. Ltd., China), TiO_2 (98.0%, Sinopharm Chemical Reagent Co. Ltd., China), and Fe_2O_3 (99.0%, Sinopharm Chemical Reagent Co. Ltd., China) were mixed in stoichiometric ratio and ball-milled for 20 h. Dry mixed powders were uniaxially pressed into pellets and then calcined at 1400 °C for 5 h in air. $\text{Sm}_{0.2}\text{Ce}_{0.8}\text{O}_{1.9}$ (SDC) powders were prepared using citric acid assisted method as reported elsewhere and calcined at 800 °C for 2 h in air [23]. X-ray diffraction (XRD, PANalytical X'Pert Power, Cu K_α radiation, $\lambda=0.15418$ nm) was performed to analyze the phase formation of the as-prepared PSTF and evaluate the phase stability of PSTF powders after treated in 50 ml min⁻¹ of 5% H_2/N_2 at 800 °C for 20 h.

Electrical conductivity of PSTF was measured using KEITHLEY 2400 Source Meter by four-probe DC technique in 5% H_2/N_2 at a flow rate of 50 ml·min⁻¹. Before test, the sample was pre-sintered at 1400 °C for 5 h in air to achieve high density.

8% $\text{Y}_2\text{O}_3\text{-ZrO}_2$ powders (China Building Materials Academy, China) were pressed into pellets and sintered at 1400 °C for 6 h in air. The thickness of YSZ electrolyte was ~ 400 μm . SDC slurry (SDC dispersed in mixed appropriate ratio of ethyl cellulose and terpenol) was spun onto one side of the YSZ electrolyte and then

sintered at 1300 °C for 4 h in air to form a barrier layer in order to prevent reaction between YSZ and PSTF materials. PSTF cathode slurry and 60wt.% LSM-YSZ anode slurry ($(\text{La}_{0.75}\text{Sr}_{0.25})_{0.95}\text{MnO}_{3-\delta}$, Ningbo SOFCMAN Energy Technology Co., Ltd) were prepared as well as SDC slurry and symmetrically printed onto the SDC side and YSZ side respectively (in the area of $\sim 0.12 \text{ cm}^2$) and then sintered at 1200 °C for 2 h in air to form YSZ electrolyte supported PSTF||SDC|YSZ||LSM-YSZ single cell. Ag paste was used as current collectors and dried at 450 °C for 30 min after painting onto both electrode surfaces. Ag reference electrode was deposited on YSZ pellet to the LSM-YSZ side with the area $< 0.02 \text{ cm}^2$. It is over 2 mm away (about 5 times to the thickness of YSZ electrolyte) from LSM-YSZ electrode edge. Fig. 1 showed configuration of the single cell. Ag wire was used as lead wire.

Electrochemical performance tests were performed at 800 °C in Ar/H₂/(20%, 40% and 60%)H₂O, with Ar and H₂ at a volume ratio of 4:1 and a total flow rate of 50 ml min⁻¹. Current density versus voltage curves (*j*-*V* curves), AC impedance spectra and cell operation durability were tested by an electrochemical workstation (Biologic VSP, France). The frequency of AC impedance spectra ranged from 100 kHz to 0.1 Hz and the AC amplitude was 10 mV. The cross-sections microstructure of the cell was analyzed using a scanning electron microscope (SEM, Hitachi, SU8000, Japan).

3. Result and Discussion

3.1 Material characterization and microstructures of the electrolyzer

XRD pattern of PSTF powders in Fig. 2 confirms a single phase of cubic perovskite structure (JCPDS: #34-0638, $a=3.8831\pm 0.0030 \text{ \AA}$, $V=58.5503\pm 0.1347 \text{ \AA}^3$). As shown in the inset of Fig. 2, no secondary phase can be found after reducing PSTF powder in 5%H₂/N₂ at 800 °C for 20 h, demonstrating the high redox stability of PSTF. At the same time, it can be seen that the peaks of PSTF after reduction slightly

shift to small angle, which can be explained as cell expansion ($a=3.9021\pm0.0016$ Å, $V=59.4172\pm0.0748$ Å³) resulted from the transition of Fe⁴⁺ (0.585 Å) to Fe³⁺ (0.645 Å) and/or Ti⁴⁺ (0.605 Å) to Ti³⁺ (0.670 Å) [24, 25]. As reported in the literature [26], a phase transformation from SrFeO_{3-δ} to Sr₂Fe₂O₅ occurred after annealing in a flow of 5%H₂/Ar at 800 °C for 24 h. In comparison, PSTF shows much better at phase stability in reducing atmosphere.

The mixed conductivity of PSTF is 0.25 S cm⁻¹ at 800 °C in 5%H₂/N₂. It is significantly higher than that of pure SrFeO₃ in 5%H₂/Ar at 800 °C, e.g. 0.03 S cm⁻¹ [27], which confirms that doping Pr enhances the conductivity of SrFeO₃-based oxide. The conductivities of common hydrogen electrode materials are listed in Table 1. PSTF possesses an acceptable electrical conductivity, and is comparable to the other hydrogen electrode materials.

Fig. 3 presents the microstructures of PSTF||SDC|YSZ||LSM-YSZ cell. The thickness of these four components is about 30, 10, 400 and 30 μm, respectively. The adhesion between each other is good. The thickness and density of SDC barrier layer can effectively separate the YSZ from PSTF materials. The submicron granularity and particles distribution both PSTF and LSM-YSZ electrode is quite uniform.

3.2 In-situ AC impedance spectra of the PSTF electrode

In-situ AC impedance spectra can be utilized to investigate the change of cell/electrode resistance under different atmosphere or current density conditions. In order to evaluate the impedance of PSTF electrode in the electrolysis process, the three-electrode method is used with PSTF electrode as working electrode and Ag electrode as reference electrode. The AC impedance data of the PSTF electrode in Ar/H₂/20%H₂O, Ar/H₂/40%H₂O, and Ar/H₂/60%H₂O under a series of applied current density from 0 to -300 mA cm⁻² are presented in Fig. 4. Ohm resistance is subtracted

in order to analyze the polarization resistance clearly. The intercept at low-frequency on the real axis corresponds to the electrode polarization resistance (R_p). There are two arcs in the impedance spectroscopy. Generally, the contributions in R_p can be distinguished using the equivalent circuit in Fig. 5: the high-frequency arc (R_H) mainly reflecting the charge transfer process at the electrode/electrolyte interface, and the low-frequency arc (R_L) relating to the steam adsorption, H_2 desorption or surface diffusion processes at the PSTF electrode inner surface[30]. It can be observed in Fig. 4 that the R_H increase slightly with the increase of steam concentration, which suggests that the concentration of steam has an insignificant influence on the charge transfer process. On the other hand, R_L is considerably increased with the increase of the H_2O content under the open circuit voltage (OCV) condition. Two causes could be involved in this phenomenon. The first is that there is a competition between the adsorption of H_2 and steam on the reactive surfaces adjacent to the three phase boundary (TPB) or in porous PSTF electrode bulk. The second is the higher gas diffusion resistance of steam compared to H_2 in the porous electrode due to its heavier molecules [31]. With increased electrolysis current density $|j|$, R_L in Ar/ H_2 /20% H_2O gradually exceeds the one in Ar/ H_2 /40% H_2O when j is -50 mA cm^{-2} and the one in Ar/ H_2 /60% H_2O when j is -150 mA cm^{-2} , which is related to steam starvation in PSTF electrode due to the species transport limitation in porous hydrogen electrode. This phenomenon is mitigated in Ar/ H_2 /40% H_2O and further thoroughly eliminating in Ar/ H_2 /60% H_2O .

The relationship between R_H , R_L and/or R_p and current density in the same feeding gas is illustrated in Fig. 6. The R_H decreasing with increasing $|j|$ owes to the enhanced charge transfer ability under larger electrolysis current. R_L decreases firstly and then increases with improved $|j|$ value for the PSTF electrode in Ar/ H_2 /20% H_2O

and Ar/H₂/40%H₂O in Fig. 6 (a) and (b), but it always keeps decreasing for the PSTF electrode in Ar/H₂/60%H₂O in Fig. 6 (c). The diminution of R_L is caused by the enhanced electro-catalytic activity under larger electrolysis current, while the raising of R_L attributes to steam starvation in porous electrode for lower H₂O concentration as stated earlier. The obtained result, moreover, shows that the R_L is larger than R_H and mass transport process is rate-determine-step (RDS) of the PSTF hydrogen electrode reaction. The overall R_p is as small as 0.42, 0.46, and 0.60 $\Omega \text{ cm}^2$ in Ar/H₂/(20%, 40% and 60%)H₂O respectively under OCV at 800 °C.

3.3 Electrochemical performance of the electrolyzer

In order to study the effect of external voltage and steam concentration on electrochemical performance of the PSTF||SDC|YSZ||LSM-YSZ cell, current density with applied voltage curves (j - V curves) was performed. Fig. 7 shows j - V curves at 800 °C, the OCV is 0.94, 0.90 and 0.87 V for hydrogen electrode in Ar/H₂/(20%, 40% and 60%)H₂O respectively, consistent with the Nernst equation, which decreases with the increase of the steam to hydrogen ratio. Positive current densities indicate power generation (SOFC mode) while negative current densities indicate power consumption (SOEC mode) [32]. From Fig. 7, in the SOFC mode, it can be seen that the biggest power density is 98.5, 76.7 and 64.2 mW cm^{-2} for PSTF electrode in H₂O partial pressure from 20% to 60%. In the SOEC mode, the relationship between the applied voltage and current density is close to but not strictly linear. Moreover, the electrolysis voltage drops with increasing vapor concentration, indicating the promotion of H₂O electrolysis that is resulting from the increase of reactants concentration. The maximal current density is -285.0, -298.2 and -302.2 mA cm^{-2} in Ar/H₂/(20%, 40% and 60%)H₂O at 1.50, 1.50 and 1.46 V, respectively. Comparison of cell performance with other common hydrogen electrode is listed in Table 2. The

electrolyzer with PSTF electrode exhibits a promising electrochemical performance.

The AC impedance spectra is also used to evaluate the electrochemical performance of the PSTF||SDC|YSZ||LSM-YSZ cell. Fig. 8, Fig. 9 and Fig. 10 shows separately the impedance spectra of the whole electrolyzer in a series of current density for the different feeding gases to the PSTF electrode. Increasing $|j|$ makes R_{ohm} obviously drop, which is attributed to the elevated cell temperature by the Joule heat for the larger current flowing through the YSZ electrolyte. The intercept at low-frequency corresponds to the total resistance (R_t). It is also noted that R_t changes under different current density that means the j - V curves in Fig. 7 are not strictly linear. Different from impedance spectra of the PSTF electrode, there are three contributions in R_p can be seen and be fitted using the equivalent circuit in Fig. 11: a high-frequency arc (R_H) for frequencies between 2.8 kHz and 100 Hz, a medium-frequency arc (R_M) for frequencies between 100 Hz and 1 Hz, and a low-frequency arc (R_L) for frequencies between 1 Hz and 0.1 Hz. Complex gas conversion and redox reaction occurs on both the hydrogen electrode and the oxygen electrode. Therefore, it is not possible to separate completely reaction process from hydrogen electrode to oxygen electrode. However, combined result of R_H and R_M mainly corresponds to the charge transfer and redox reaction process on two electrodes, which decreases with improved $|j|$ in the same H_2O concentration respectively. Consistent with the PSTF electrode, this phenomenon suggests the enhanced electro-catalytic activity under larger electrolysis current. Moreover, R_L mainly corresponds to the gas dissociative, adsorption and diffusion process of H_2/H_2O in PSTF electrode and O_2 in LSM-YSZ electrode[37, 38]. And it grows with increasing $|j|$ in the same H_2O concentration. In $Ar/H_2/20\%H_2O$, the value of R_L increases sharply when $|j|$ is larger than 200 mA cm^{-2} which is from mass transport

limitation. While mass transport limitation improves when higher H₂O content fed to the PSTF electrode so that growth rate of the R_L reduces with the steam concentration from 20% to 60%. Compared to the literature values as listed in Table 2, the cell with PSTF electrode shows a competitive polarization resistance.

In order to evaluate the durability of the SOEC with PSTF as hydrogen electrode, the relationship of terminal voltage and run time under the constant electrolysis current density of -200 mA cm^{-2} is tested with Ar/H₂/60%H₂O at 800 °C. As shown in Fig.12, the cell voltage is about 1.3 V and rises as small as $\sim 2.0\%$ during 20 h running. The delamination between LSM-YSZ oxygen electrode and YSZ electrolyte maybe the main reason for rising of the electrolysis voltage after long time operation [39, 40]. Compare to the LSCM-YSZ hydrogen electrode, the voltage increased by 8.2% of the cell operated at a constant electrolysis current density of -0.33 A cm^{-2} with 45 vol.% AH and 30 ml min^{-1} H₂ as carrier gas at 850 °C [31], the cell with PSTF electrode possess basically electrochemical stability in the electrolysis operations.

4. Conclusion

A-site and B-site co-doped strontium ferrite perovskite oxide $\text{Pr}_{0.3}\text{Sr}_{0.7}\text{Ti}_{0.3}\text{Fe}_{0.7}\text{O}_{3-\delta}$ has been successfully prepared by solid state reaction method, and are successfully used as cathode of electrolyte support PSTF||SDC||YSZ||LSM-YSZ electrolyzer. Its conductivity is 0.25 S cm^{-1} at 800 °C in 5% H₂/N₂, which is 8 times greater than pure SrFeO₃. Favorable performance is obtained at the single cell for H₂O electrolysis at 800 °C. The current density is $-302.2 \text{ mA cm}^{-2}$ and the polarization resistance of the electrolyzer is $0.7 \text{ } \Omega \text{ cm}^2$ at an applied voltage of 1.46 V in Ar/H₂/60%H₂O. The corresponding polarization resistance of PSTF electrode is as small as $0.25 \text{ } \Omega \text{ cm}^2$, which accounts for 36% of

total polarization resistance. PSTF exhibits both higher chemical stability after dealing in 5% H_2/N_2 at 800 °C for 20 h from XRD analysis, and basically electrochemical stability under reducing gas and larger current density during 20 h running. In conclusion, perovskite oxide $\text{Pr}_{0.3}\text{Sr}_{0.7}\text{Ti}_{0.3}\text{Fe}_{0.7}\text{O}_{3-\delta}$ is a promising hydrogen electrode material for H_2O electrolysis in SOEC. At the same time, by optimizing the structure of the electrolyzer and introducing catalysts into the PSTF electrode, the electrochemical performance will be further improved.

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Fig. 1. The structure diagram of the PSTF||SDC|YSZ||LSM-YSZ single cell.

Fig. 2. XRD patterns of the prepared PSTF and after exposed to 5% H_2/N_2 at 800 °C for 20h.

Fig. 3. SEM images of the PSTF||SDC|YSZ||LSM-YSZ electrolysis cell with the PSTF cathode (a) and LSM anode (b).

Fig. 4. AC impedance spectra of the PSTF electrode in different H_2O concentration under a series of current density at 800 °C.

Fig. 5. The equivalent circuit for AC impedance spectra fitting of PSTF electrode at 800 °C.

Fig. 6. The change trend of the fitting R_H , R_L , and R_p with electrolysis current density in $\text{Ar}/\text{H}_2/(20\%, 40\%, 60\%) \text{H}_2\text{O}$ at 800°C .

Fig. 7. j - V curves of the PSTF||SDC|YSZ||LSM-YSZ single cell in different atmosphere at 800 °C.

Fig. 8. Cell impedance spectra with different current density for H₂O electrolysis in Ar/H₂/20%H₂O at 800 °C. (a) Complex plane and (b and c) Bode presentations.

Fig. 9. Cell impedance spectra with different current density for H_2O electrolysis in $\text{Ar}/\text{H}_2/40\%\text{H}_2\text{O}$ at 800°C . (a) Complex plane and (b and c) Bode presentations.

Fig. 10. Cell impedance spectra with different current density for H_2O electrolysis in $\text{Ar}/\text{H}_2/60\%\text{H}_2\text{O}$ at 800°C . (a) Complex plane and (b and c) Bode presentations.

Fig. 11. The equivalent circuit for AC impedance spectra fitting of the
PSTF||SDC|YSZ||LSM-YSZ cell at 800 °C.

Fig. 12. The change of electrolyzer terminal voltage vs. time for PSTF electrode in Ar/H₂/60% H₂O at 800 °C when j is -200 mA cm^{-2} .

Table 1. Total conductivity of several common hydrogen electrode materials.

Material	Atmosphere	T (°C)	Conductivity (S cm^{-1})
PSTF	5% H_2/N_2	700	0.10
		750	0.17
		800	0.25
$\text{SrFe}_{0.75}\text{Ti}_{0.25}\text{O}_{3-\delta}$	5% H_2/Ar	700	0.8 [27]
$\text{Sr}_{0.92}\text{Y}_{0.08}\text{Ti}_{0.7}\text{Fe}_{0.3}\text{O}_{3-\delta}$	H_2	800	0.56 [28]
$\text{La}_{0.5}\text{Sr}_{0.5}\text{Fe}_{0.5}\text{Ti}_{0.5}\text{O}_{3-\delta}$	5% $\text{H}_2/95\%\text{N}_2$	900	<0.10 [12]
$\text{La}_{0.75}\text{Sr}_{0.25}\text{Cr}_{0.5}\text{Mn}_{0.5}\text{O}_{3-\delta}$	5% H_2/Ar	700	0.693 [29]
$\text{La}_{0.75}\text{Sr}_{0.25}\text{Cr}_{0.5}\text{Mn}_{0.4}\text{Sc}_{0.1}\text{O}_{3-\delta}$			0.185 [29]

Table 2. The electrochemical performance of several different electrolysis cells.

Hydrogen Electrode	Cell structure	V (V)	T (°C)	Feed gas	j (mA cm^{-2})	R_p ($\Omega \text{ cm}^2$)
$\text{Pr}_{0.3}\text{Sr}_{0.7}\text{Ti}_{0.3}\text{Fe}_{0.7}\text{O}_{3-\delta}$	PSTF SDC YSZ(400 μm) LSM-YSZ	1.50	800	Ar/H ₂ /20%H ₂ O	285	>1.75
		1.50		Ar/H ₂ /40%H ₂ O	298	0.99
		1.46		Ar/H ₂ /60%H ₂ O	302	0.70
Ni-YSZ	Ni-YSZ YSZ LSM(HTCeramix)	1.16	800	50 vol.% AH	560	0.45[33]
$\text{La}_{0.75}\text{Sr}_{0.25}\text{Cr}_{0.5}\text{Mn}_{0.5}\text{O}_{3-\delta}$	LSCM-YSZ YSZ(300 μm) LSM-YSZ	1.213	800	40 vol.% AH	120	0.9[8]
$\text{La}_{0.75}\text{Sr}_{0.25}\text{Cr}_{0.5}\text{Mn}_{0.5}\text{O}_{3-\delta}$	LSCM-YSZ YSZ(15 μm) LSM	1.66	850	45 vol.% AH	330	0.7[34]
$(\text{La}_{0.3}\text{Sr}_{0.7})_{0.9}\text{Ti}_{0.9}\text{Ni}_{0.1}\text{O}_{3-\delta}$	LSTN-SDC YSZ(2mm) LSM-SDC	1.6	800	3%H ₂ O/5%H ₂ /Ar	60	5.8[35]
$\text{La}_{0.3}\text{Sr}_{0.7}\text{TiO}_{3+\delta}$	LSTO YSZ(2mm) LSM-YSZ	1.5	900	47%H ₂ O/3%H ₂ /50%Ar	85	1.4[36]

Note: part of the data is observed from the pictures in the references.