Tailoring the electrolyte and cathode properties for optimizing the performance of symmetrical solid oxide fuel cells fabricated by one-step co-sintering method

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ABSTRACT
Symmetrical solid oxide fuel cells (S-SOFCs) are prepared via a facile one-step co-sintering method with highly reactive Sm$_{0.2}$Ce$_{0.8}$O$_{1.9}$ (SDC) electrolyte and Sr$_2$Fe$_{1.5}$Mo$_{0.5}$O$_{6.6}$ (SFM) electrodes. The phase compositions and microstructures are studied by XRD, TEM, and FESEM techniques, and the electrolyte-supported single cells with gas-tight SDC electrolyte and porous SFM-SDC electrode are prepared after one-step co-sintering at 1100 °C or higher temperatures for 4 h. In particular, the AC impedance spectra reveal that the SDC electrolyte sintered at 1200 °C exhibits the highest oxide ionic conductivity of ~35 mS/cm at 700 °C, while the electrode polarization resistance achieves the lowest value of 0.32 Ω-cm$^2$ at 700 °C in air for the sample co-sintered at 1100 °C. Accordingly, the output measurements are carried out on the single cells co-sintered at 1100 °C and 1200 °C. It is found that the single cell co-sintered at 1200 °C possesses the highest peak power density of 216 mW/cm$^2$ at 700 °C, demonstrating the potential application of the one-step co-sintering method in low-cost manufacturing of S-SOFCs.

1. Introduction
Solid oxide fuel cells (SOFCs) have received wide attention due to a series of advantages, such as high efficiency, low environmental impact, and fuel flexibility [1,2]. To achieve the optimal configuration of porous anode|densiﬁed electrolyte|porous cathode, typical SOFCs preparation process usually includes at least two annealing steps due to the different compositions and microstructure of electrode and electrolyte materials. However, the complex procedures and the heating/cooling cycles in cell fabrication will consume much time and energy which are undesirable from a commercial point of view. Therefore, the co-sintering of triple-layered SOFCs in one thermal circle is of great interest, because it can effectively reduce the preparation process and thus realize the desired low-cost manufacturing process for SOFCs [3–5].

The major challenge for this approach is to reduce the densification temperature of electrolyte, so as to minimize the phase reactions between electrolyte and electrode as well as inhibit the destruction of the porous electrode structure during co-sintering process of single cell. The utilization of sintering aids to boost the sintering performance of electrolyte has been demonstrated to be an effective way. Dai et al. employed Co as sintering aids to boost the sintering performance of Sm$_{0.2}$Ce$_{0.8}$O$_{1.9}$ (SDC) electrolyte and then obtained the electrolyte-supported single cell after co-sintering at 1100 °C. The peak power density of single cell is about 289 mW/cm$^2$ at 700 °C [6]. In another case, Zhang et al. fabricated an anode-supported single cell at the co-sintering temperature of 800 °C by adding 1.5 mol% LiNO$_3$ into the Ce$_{0.2}$Gd$_{0.2}$Y$_{0.15}$O$_{1.9}$ (GYDC) electrolyte. However, the authors proposed that such a low temperature is detrimental to the interface between the phases of electrode and electrolyte, which leads to the high ohmic and polarization resistances as well as poor fuel cell performance [7].

In fact, the studies addressing the relationship between calcination temperature and the electrochemical performance of electrode have revealed that the electrode performances strongly depend on the calcination temperature [8–10]. For instance, the GdBaCo$_2$O$_{5+δ}$ cathode obtained after calcination at 900 °C exhibited the higher over-potential within the current range investigated and the larger polarization resistance than that sintered at 1050 °C [11]. In another instance, the electrode polarization resistances of Sr$_2$Fe$_{1.5}$Mo$_{0.5}$O$_{6.6}$ decrease at first and then increase as the calcination temperature is improved from 900 °C to 1200 °C, with the samples synthesized at 1000 °C showing the lowest electrode polarization resistance of 0.076 Ω-cm$^2$ at 800 °C [12]. In addition to the electrode, the oxide ionic conductivity of electrolyte is closely related to sintering temperatures [13,14]. Taking the highly densified SDC electrolyte as an...
example, as the sintering temperature is decreased from 1400 °C to 1100 °C, the oxide ionic conductivity is increased first and then decreased, with the sample sintered at 1200 °C showing the highest ones [15]. Thereby, from the perspective of optimizing the cell performance, seeking the appropriate co-sintering temperature to optimize the electrochemical performances of electrolyte and electrode is another key issue of one-step co-sintering process.

For the purpose of optimizing the cell performance through tuning the co-sintering temperature, Dai et al. investigated the electrochemical performances of SDC-based single cells co-sintered at a series of temperatures. It has been demonstrated that the higher co-sintering temperature is beneficial to decrease the ohmic resistances of single cells; however, it significantly enhances the electrode polarization resistances. Accordingly, the single cell co-sintered at 1000 °C with the lowest electrode polarization resistance of 0.019 Ω·cm² at 700 °C shows the highest peak power density of 401 mW/cm² at 700 °C [16]. Bi et al. prepared an anode supported SOFC after one-step co-sintering at 1150 °C–1350 °C and declared that the cell co-sintered at 1250 °C showed the best peak power density of 160 mW/cm² at 700 °C, due to the lowest ohmic resistance and reasonable electrode polarization resistance [17].

However, to our best knowledge, the application of the one-step co-sintering process to the investigation of symmetrical SOFCs has not been reported. Thereby, the symmetrical SOFCs constructed by SDC electrolyte and Sr₂Fe₃Mo₆₃O₇·δ (SFM) symmetrical electrode was synthesized via one-step co-sintering method. In particular, focusing on the above-mentioned two key issues, the highly sintering active SDC powders were first synthesized by ammonium carbonate precipitation method, and then the single cells with SFM symmetrical electrodes were synthesized via one-step co-sintering method at 1100 °C–1300 °C. In order to seek the appropriate co-sintering temperature, the effects of sintering temperatures on the phase compositions, microstructural features, and electrochemical performances of SDC electrolyte and SDC-SFM composite electrode were studied. Finally, the output performances and electrochemical behavior of the single cell were investigated.

2. Experimental

2.1. Powder synthesis

Highly reactive SDC powder was prepared via ammonium carbonate co-precipitation and subsequent calcination processes. In a typical preparation process, cerium nitrates and samarium nitrates were dissolved in 150 mL deionized water to form a 0.1 M metal ion solution. Afterward, 300 mL ammonium carbonate aqueous solution with the concentration of 0.1 M was directly added into cerium-samarium nitrates solution under vigorous stirring. The precipitate was separated through vacuum filtration, along with washing three times with deionized water and alcohol, respectively. Finally, the as-obtained precipitate was dried at 80 °C in an oven, followed by calcination at 500 °C for 2 h.

SFM powder was synthesized through a glycine combustion process [18]. Sr(NO₃)₂, Fe(NO₃)₃ · 9H₂O, and (NH₄)₆Mo₇O₂₄ · 4H₂O were first dissolved in glycine solution under vigorous stirring at 80 °C. Afterward, according to the molar ratio of 1:2:1.5 for metal cations:glycine:citric acid (CA), CA was added to the suspension, which was continuously stirred at 80 °C to obtain the transparent gel. After drying in oven at 250 °C, the as-obtained black product was calcined at 1200 °C for 5 h to afford SFM powder.

2.2. Electrolyte and cell fabrication

To prepare electrolyte pellets for oxide ionic conductivity measurement, the SDC powder mixed with polyvinyl alcohol as binder was pressed into green pellets with diameter of 13 mm before sintering at 1100, 1200, and 1300 °C for 4 h. According to the sintering temperature, the SDC electrolytes are denoted as SDC-1100, SDC-1200, and SDC-1300, respectively.

For the sake of preparing symmetrical cells for electrode polarization resistance and output performance measurements, as shown in Figure S1, 0.2 g SDC powder was uniaxially pressed into disc-like green pellet. Subsequently, the composite electrode powders consisting of the phases of SDC and SFM with the weight ratio of 2:3 were mixed with terpineol to obtain the composite electrode slurry. Hereinto, the addition of SDC into SFM can effectively tune the thermal expansion coefficient (TEC) value of electrodes, since the TEC of the SFM is much higher than that of SDC [19,20], so as to realize better thermal matching between electrode and electrolyte and then ensure the successful implementation of the one-step co-sintering process. Finally, the composite electrode slurry was brush-painted on both sides of green pellets, which were co-sintered at 1100, 1200, and 1300 °C for 4 h with the heating rate of 3 °C/min, and then cooled down to 700 °C at 2 °C/min to afford the single cells, which were expressed as Cell-1100, Cell-1200, and Cell-1300, respectively.

2.3. Characterizations

The phase composition was studied by using an X-ray diffractometer (XRD, SmartLab, 40 kV/30 mA, λ = 1.5418 Å/Cu Kα). The microstructures were observed by using an electron microscope (SEM/TEM, JEOL, JSM-7610 F/JSM-2100). The relative densities of SDC electrolytes were measured by the Archimedes
method. To investigate the oxide ionic conductivities, the SDC pellets coated with Ag paste were measured on a CHI 660E electrochemical work station by using the AC impedance spectrum method. The measurement was performed in the frequency range of 0.1 Hz ~ 0.1 MHz from 500 °C to 700 °C in air. For evaluating the electrode polarization resistance, the EIS curves of symmetrical cell coated with Ag paste were recorded at the temperature ranging from 600 °C to 700 °C in air, within the frequency ranging from 0.1 Hz to 0.1 MHz and the amplitude of 10 mV in air. In order to study the fuel cell performance, the button cells co-sintered at different temperatures with an effective area of ~0.28 cm² were coated with silver paste on both sides and then sealed with Ag paste. The measurement was carried out at the temperatures from 600 °C to 700 °C. The flow rate of hydrogen fuel on the anode side is about 40 mL/min and the cathode side of button cell is directly exposed to air. The EIS curves of single cell were recorded at the open circuit voltage (OCV) condition within the frequency ranging from 0.1 Hz to 0.1 MHz and the amplitude of 10 mV.

3. Results and discussions

3.1. Phase composition and microstructures of the as-obtained samples

The phase composition of SDC powder was examined by room-temperature X-ray diffraction (XRD). As shown in Figure 1(a), all diffraction peaks of SDC powder are aligned with those of cubic fluorite-structured SDC phase referenced to JCPDS card no. 75-0158, without any formation of impurity phases. Moreover, as shown in Figure 1(b) and (c), the SDC powder consists of discrete granular particles and according to count the sizes of 100 particles by using the software of Nanomeasure 1.2, the average size of particles is about 20~30 nm. After powder pressing and then sintering at different temperatures for 4 h, as shown in Figure 1(a), the as-obtained SDC electrolyte exhibited similar diffractions peaks to their powder precursor, regardless of the differences in line shape due to the grain growth in sintering process.

The foundation of one-step co-sintering preparation of SOFCs is reducing the densification temperature of electrolyte, and according to Figure S2, the relative densities of SDC electrolyte sintered at the temperature above 1100 °C are all higher than 92%, fulfilling the gas-tight expectation of electrolyte. Such excellent sintering behavior of SDC powder prepared by ammonium carbonate precipitation method is consistent with previous reports [15,21,22], which should be related to the nanoscale and discrete granular particles morphologies. Moreover, as shown in Figure 1(d, f), the samples of SDC-1100, SDC-1200, and SDC-1300 exhibit similar microstructures with polygonal grains and the grains show a significant increase with the increased sintering temperature. Specifically, the average grain sizes based on counting the sizes of 100 particles by using the software of Nanomeasure 1.2 are about 0.21, 0.30, and 1 μm for the SDC-1100, SDC-1200, and SDC-1300, respectively.

Figure 2(a) presents the XRD pattern of the SFM powder fabricated by glycine combustion method, demonstrating the formation of pure perovskite phase after the precursor is fired at 1200 °C for 5 h. Furthermore, the SFM phase reduced in H2 at 750 °C for 2 h maintained the perovskite structure, demonstrating its good stability in the reducing atmosphere, which should be ascribed to the Mo5+/Mo6+ redox band overlaps with the Fe3+/Fe2+ couple [23]. Besides

![Figure 1](image)

Figure 1. XRD patterns of SDC powders and SDC electrolyte sintered at different temperatures (a); TEM (b) and the second electron (SE) model SEM (c) micrographs of SDC powders; the second electron (SE) model SEM micrographs of SDC electrolytes sintered at 1100 °C (d), 1200 °C (e), and 1300 °C (f), respectively.
Figure 2. (a) XRD patterns of SFM and reduced-SFM samples; (b) XRD patterns of SFM-SDC composite electrode obtained after calcination at different temperatures; cross-sectional SEM images of the electrolyte/electrode interface of the cell co-sintered at 1100 °C (c), 1200 °C (d), and 1300 °C (e) under the second electron (SE) model, respectively; the second electron (SE) model SEM images of SFM-SDC composite electrode co-sintered at 1100 °C (f), 1200 °C (g) and 1300 °C (h), respectively; and (i) SEM image and elemental distribution maps of SFM-SDC electrode layer co-sintered at 1100 °C.

that, the peaks of SFM slightly shift to the lower angle range after the reduction treatment, in agreement with previous reports, which should be caused by the reduction of iron and molybdenum ions [24–26].

The phase reactions between SDC and SFM phases are unfavorable for the preparation of SOFC by one-step co-sintering process, which may produce highly resistive phases and thus deteriorate the fuel cell performance. For the sake of evaluating the chemical compatibility between SDC and SFM, the composite electrode was calcined at the temperatures from 1100 °C to 1300 °C, and as revealed by Figure 2(b), only the peaks associated with the phases of SFM and SDC were detected in the XRD patterns. This result suggests that there are no obvious phase reactions between SDC and SFM within the investigated temperature range, demonstrating that SFM materials exhibit good chemical compatibility with SDC within the investigated temperature range.

The co-sintering temperature is considered to affect the microstructural features of electrode and electrode/electrolyte interface, which in turn influence the electrochemical performances of electrodes. First, as shown in Figure 2(c–e), the electrodes in all three samples adhered well to the electrolyte layer without obvious cracks and delamination; however, the significant grain growth and decrease in porosity with the increased co-sintering temperature can be well identified. Specifically, it can be found from Figure 2(f–h) that some small agglomerated particles appear to be tightly embedded on the surface of large particles in Cell-1100 and Cell-1200. As the temperature increases to 1300 °C, the particle size increases significantly and a clear necking connection among particles can be noticed, which may reduce the reaction area and raise the resistance to gas diffusion. In addition, according to the energy-dispersive X-ray spectrometer (EDS) measurement on the sample of Cell-1100 shown
3.2. Oxide ionic conductivities of electrolytes sintered at different temperatures

The electrolyte layer in solid oxide fuel cell not only acts as a gas barrier but also directly determines the output performances of single cell. With respect to the fact that the sintering temperature significantly affects the microstructural features of SDC electrolyte, especially in terms of average grain size which is closely associated with the oxide ionic conductivity, the AC impedance analysis was used to determine the electrical conductivities of SDC electrolyte, so as to evaluate the relationships between the sintering temperature and the oxide ionic conductivity of SDC electrolyte.

Figure 3 represents the AC impedance spectra of SDC-1200 at the temperatures ranging from 500 to 700 °C in air and those for SDC-1100 and SDC-1300 are given in Figures S4 and S5. As can be seen in Figure 3(a), the impedance spectrum at 500 °C consists of the arcs related to the electrode process, while the arcs associated with the grain and grain boundary processes disappear. This should be ascribed to the fact that the increased temperature improves the characteristic frequencies of grain and grain boundary processes and then exceeds the upper frequency limit of the instrument used. As the measured temperature increases to 600 °C or higher, the entire spectrum shifts toward the lower resistance range, representing an improved ionic conductivity with increased temperature. Based on the above discussions, the AC impedance data were fitted via the equivalent circuits inserted in Figure 3(a–c) by using Zview 2, where R stands for the total oxide ionic resistances, R₁ and R₂ are the electrode resistances, and CPE₁ and CPE₂ are the constant phase elements for the electrode processes, respectively. Afterward, the oxide ionic conductivities were calculated by \( \sigma = \frac{L}{RS} \), in which L is the thickness of sample, R is the total oxide ionic resistance, and S represents the surface area of Ag electrode, respectively.

Figure 3(d) shows the overall oxide ionic conductivities of the samples of SDC-1100, SDC-1200, and SDC-1300. It can be noted that the total conductivities appear to increase first and then decrease with the increased sintering temperatures, and the oxide ionic conductivities of SDC-1100, SDC-1200, and SDC-1300 are 32 ± 1, 35 ± 1, and 30 ± 2 mS/cm at 700 °C, respectively. Moreover, the activation energies of SDC-1100, SDC-1200, and SDC-1300 are about 70.07, 67.85, and 66.98 kJ/mol, respectively. Obviously, from the perspective of oxide ionic conductivity for SDC electrolyte, the sintering temperature of 1200 °C should be preferred. In addition, the changing trend of electrical conductivity with sintering temperature is similar to those previously reported [14–16], which should be mainly contributed by the distinct electrical conductivity contributions of grain boundary.

For the sake of differentiating their grain and grain boundary conductivities, the AC impedance spectra at 200 °C for these three electrolytes were recorded and given in Figures 3(e), S3(d), and S4(d). It can be seen

![Figure 3](image-url)
that as the measurement temperature was cut down to 200 °C and the frequency range was adjusted to 0.1 Hz to 1 MHz, the arcs associated with grain and grain boundary processes could be clearly identified [27,28], and correspondingly, the resistances for grain and grain boundary can be fitted by using the equivalent circuit illustrated in the inset of Figure 3(e). Accordingly, the grain and apparent grain boundary conductivities of SDC electrolyte can be obtained. It can be found from Table S1 and Figure 3(f) that the grain conductivities of the three samples at 200 °C are very close, while the changing trend of apparent grain boundary conductivity is consistent with the total oxide ionic conductivity. This result proves that grain boundary conductivity plays a key role in the electrical behavior of SDC electrolyte.

In order to evaluate the influence from sintering temperature on the conduction behavior of SDC electrolyte, especially the grain boundary, the specific grain boundary conductivity representing the real conduction property of grain boundary was estimated. The detailed calculation process is shown in the Supporting Information. As can be seen in Figure 3(f), the specific grain boundary conductivities decrease with the sintering temperatures. Such variation can be related to the contributions from the interfacial space charge potential, which is related to the dopant segregation at grain boundary [29,30]. The higher sintering temperature leads to an increase in grain size, as revealed by SEM micrographs, and thus less grain boundary area for dopant segregation. Correspondingly, on one hand, as the sintering temperature is increased from 1100 to 1300 °C, the degree of segregated dopants along grain boundary is expected to be promoted, leading to the higher space charge layers and lower specific grain boundary conductivity, which is unfavorable for the transport of oxide ions across grain boundary. On the other hand, the reduced low conductivity grain boundary area is beneficial for improving the oxide ionic conductivity. Therefore, the apparent grain boundary conductivity and even the total oxide ionic conductivity are increased with sintering temperature to a maximum value and then decreased.

### 3.3. Electrode performances of single cell in air

In order to evaluate the effect of the co-sintering temperature on the electrochemical properties of electrode, the AC impedance spectra of Cell-1100, Cell-1200, and Cell-1300 were recorded at the temperatures of 600–700 °C in air. Figure 4 represents the AC impedance spectra obtained at 700 °C in air and those for the other temperatures are given in Figure S6. One can see from Figure 4(a–c) that the impedance spectra include two depressed arcs in high and low frequency ranges, which can be quantitatively analyzed by fitting the AC impedance data by the equivalent circuit of $LR_o/Q_H$

![Figure 4](image_url)

**Figure 4.** AC impedance spectra of the single cell obtained after co-sintering at different temperatures (a) 1100 °C, (b) 1200 °C, and (c) 1300 °C at 700 °C; (d) the measured temperature-dependent electrode polarization resistances of the sample co-sintered at different temperatures; (e) the $R_o$ and $R_i$ of Cell-1100, Cell-1200, and Cell-1300, respectively. Representative frequencies in the EIS spectra are marked with solid points, and the unit of frequency is hertz.
$R_{\mu}(Q_i R_i)$. Here, $L$ is the inductance, $R_o$ is the ohmic resistance, $R_i$ and $Q_i$ ($i=H, L$) represent the resistance and constant phase element of the contributions at high and low frequencies, respectively, and thus the electrode polarization resistance ($R_p$) can be expressed as $R_p = R_{\mu} + R_i$. Moreover, the $R_p$ was subtracted in Nyquist plots, so as to directly compare the differences in electrode performances of these three cells.

As shown in Figure 4(d), the $R_p$ value is increased along with the increasing co-sintering temperature, and specifically, the $R_p$ value of Cell-1100 is $0.32 \Omega \cdot \text{cm}^2$ at 700 °C which is slightly lower than that of Cell-1200 (0.33 $\Omega \cdot \text{cm}^2$), while the Cell-1300 exhibits remarkably enhanced $R_p$ value, which is about 0.49 $\Omega \cdot \text{cm}^2$. On one hand, this result suggests that the elevated higher co-sintering temperature of 1300 °C is unfavorable for boosting the electrode performance; On the other hand, the $R_p$ of Cell-1100 and Cell-1200 is well comparable with prior SFM based cathodes, such as SFM-SDC composite cathode (0.27 $\Omega \cdot \text{cm}^2$ at 750 °C) [31] and Sr$_2$Fe$_{15}$MoO$_{40}$Nb$_{0.1}$O$_{6.5}$ cathode (0.375 $\Omega \cdot \text{cm}^2$ at 700 °C) [32], indicating that the one-step co-sintering approach not only effectively simplifies the preparation process of SOFCs but also maintains the electrochemical performances of electrode in air.

For the purpose of better understanding the effect of co-sintering temperature on electrode performance, the equivalent capacitance ($C$) and relaxation frequency ($\ell$) associated with $(Q_i R_i)$ and $(Q_i R_i)$ components were calculated, so as to distinguish the electrode process [33,34]. The detailed calculation process is given in the Supporting Information. The equivalent capacitances and the relaxation frequency of the high and low frequency processes are on the orders of magnitude of $10^{-4}$ to $10^{-2}$ F $\cdot$ cm$^{-2}$, and $10^{-1}$ to $10^1$ Hz, respectively. Thus, the high frequency range and low frequency range should be assigned to the electrode process the electron transfer and the adsorption, dissociation and diffusion process of oxygen on the electrode, respectively [35–37].

According to the fitting analysis, the $R_{\mu}$ and $R_i$ of Cell-1100, Cell-1200, and Cell-1300 are 0.20/0.12, 0.17/0.16, and 0.04/0.45 $\Omega \cdot \text{cm}^2$ at 700 °C, respectively. Specifically, the $R_{\mu}$ is decreased with the rising co-sintering temperature, indicating that the enhanced co-sintering temperature is favorable for the charge transfer process, which should be related to the optimized connection among the electrode particles and the adhesion in the electrode and electrolyte. However, as the co-sintering temperature is increased to 1300 °C, the significant grain coarsening and decrease in porosity, as revealed by SEM micrographs, are believed to improve the resistance of oxygen surface adsorption and diffusion and thereby lead to a remarkably enhanced $R_i$ [38,39].

3.4. Output performances of the single cells co-sintered at different temperatures

According to the above discussions, the Cell-1100 and Cell-1200 exhibit relatively lower oxide ionic resistance and electrode polarization resistance, and thus their output performances are checked. First, as shown in Figure 5(a) and (b), the samples of both Cell-1100 and Cell-1200 express similar microstructural features, that is, the electrode layer with a thickness of ~60 μm is adhered well to the electrolyte layer with a thickness of ~400 μm. Moreover, the open circuit voltages of Cell-1100 and Cell-1200 are about 0.82 V at 700 °C, which are lower than theoretical ones mainly due to the reduction of Ce$^{4+}$ in reducing atmosphere. Additionally, the peak power densities of Cell-1100 and Cell-1200 are about 201 and 216 mW/cm$^2$ at 700 °C, respectively, which can be well comparable with prior symmetrical SOFCs, as shown in Table 1, indicating that the one-step co-sintering method is a potential way to prepare low-cost symmetrical SOFCs with desired performances.

To further study the electrochemical performances of single cells under fuel cell testing conditions, the impedance spectra obtained in open circuit condition for these three cells are recorded at 700 °C and given in Figure 5(e). The intercept with real axis at high frequencies denotes the ohmic resistances of single cells ($R_o$), mainly consisting of the contributions from electrolyte resistance and interfacial contact resistance. And the difference between the high and low frequency intercepts with the real axis is regarded as the electrode polarization resistances ($R_p$) of single cells. As shown in Figure 5(f), the $R_p$ and $R_o$ values for the Cell-1100 and Cell-1200 at 700 °C are about 0.15/0.55 and 0.13/0.53 $\Omega \cdot \text{cm}^2$, respectively. On one hand, the lower $R_o$ for the Cell-1200 may be mainly attributed to the higher oxide ionic conductivity of electrolyte layer. On the other hand, unlike the results of the electrode polarization resistance obtained in air, the $R_p$ of Cell-1200 under fuel cell conditions is smaller than that of Cell-1100. This may be because of the fact that the catalytic ability of SFM-SDC composite electrode toward hydrogen oxidation reactions is also related to the co-sintering temperatures [45], and the Cell-1200 exhibits boosted catalytic ability than Cell-1100 might due to better connection with the electrolyte and then possesses decreased total electrode polarization resistance of entire cell worked under fuel cell condition.

Moreover, it can be found that the polarization resistances of Cell-1100 and Cell-1200 are dominated by $R_o$, about 4 times higher than $R_p$. Thereby, further enhancement on cell performances may be achieved by decreasing the thickness of electrolyte layer, so as to reduce the ohmic resistance of single cell. In the case of the single cell with a thin GDC electrolyte layer
of 80 μm, the $R_o$ is about 0.22 Ω·cm$^2$ at 700 °C [46]. In addition to reduce the thickness of electrolyte, the microstructure of electrode needs to be further optimized through adding some pore forming agent, utilizing solution infiltration method or developing new types of electrodes, so as to decrease the resistance of oxygen surface adsorption and diffusion [47–51]. Thereby, preparing the single cell with optimized electrode microstructure and thinner electrolyte via one-step co-sintering preparation will be developed in our further works.

4. Conclusions

In summary, the symmetrical single cell with highly densified SDC electrolyte and porous SDC-SFM electrode can be successfully prepared through one-step co-sintering method. The electrochemical performances of SDC electrolyte and SDC-SFM electrode can be controlled by the co-sintering temperatures, mainly due to the differences in sintering temperature-dependent microstructures. Specifically, the SDC electrolyte sintered at 1200 °C shows the highest oxide...
ionic conductivity of 35 mS/cm at 700 °C, while the electrode co-sintered at 1100 °C exhibits the lowest values of 0.32 Ω·cm² at 700 °C in air, respectively. Moreover, the single cell co-sintered at 1200 °C could achieve the appreciable peak power densities of 216 mW/cm² at 700 °C.

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Disclosure statement
No potential conflict of interest was reported by the author(s).

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Supporting information
Supporting information consisting of the fabrication process of single cell via the one-step co-sintering strategy, the relative densities of SDC electrolyte sintered at different temperatures, the elemental distribution maps of SFM-SDC electrode layer co-sintered at 1200 and 1300 °C, the AC impedance spectra for SDC-1100 and SDC-1300 electrolytes, the determination process of specific grain boundary conductivities of SDC electrolytes, the AC impedance spectra for Cell-1100, Cell-1200, and Cell-1300 at the temperatures of 600 °C and 650 °C in air, the calculation process of the equivalent capacitance (C) and relaxation frequency (f) associated with $(Q_n R_i)$ and $(Q_n R_i)$ components and the output performances of Cell-1300.

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