



Significant impact of the current collection material and method on the performance of $\text{Ba}_{0.5}\text{Sr}_{0.5}\text{Co}_{0.8}\text{Fe}_{0.2}\text{O}_{3-\delta}$ electrodes in solid oxide fuel cells

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ARTICLE INFO

Article history:

Received 5 January 2011
Received in revised form 17 February 2011
Accepted 18 February 2011
Available online 26 February 2011

Keywords:

Current collector
Barium strontium cobalt ferrite
Surface conductivity
Solid oxide fuel cells
Electrode performance

ABSTRACT

The effects of the current collection material and method on the performance of SOFCs with $\text{Ba}_{0.5}\text{Sr}_{0.5}\text{Co}_{0.8}\text{Fe}_{0.2}\text{O}_{3-\delta}$ (BSCF) cathodes are investigated. Ag paste and LaCoO_3 (LC) oxide are studied as current collection materials, and five different current collecting techniques are attempted. Cell performances are evaluated using a current–voltage test and electrochemical impedance spectra (EIS) based on two types of anode-supported fuel cells, i.e., $\text{NiO} + \text{SDC}|\text{SDC}|\text{BSCF}$ and $\text{NiO} + \text{YSZ}|\text{YSZ}|\text{SDC}|\text{BSCF}$. The cell with diluted Ag paste as the current collector exhibits the highest peak power density, nearly 16 times that of a similar cell without current collector. The electrochemical characteristics of the BSCF cathode with different current collectors are further determined by EIS at 600 °C using symmetrical cells. The cell with diluted Ag paste as the current collector displays the lowest ohmic resistance ($1.4 \Omega \text{cm}^2$) and polarization resistance ($0.1 \Omega \text{cm}^2$). Meanwhile, the surface conductivities of various current collectors are measured by a four-probe DC conductivity technique. The surface conductivity of diluted Ag paste is 2–3 orders of magnitude higher than that of LC or BSCF. The outstanding surface conductivity of silver may reduce the contact resistance at the current collector/electrode interface and, thus, contributes to better electrode performance.

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1. Introduction

In recent years, increasing attention has been paid to the development of alternative energy sources because petroleum reserves are believed to be exhausted in the next few decades. As high-temperature electrochemical energy conversion devices with advantageous features of high efficiency, low emissions and fuel flexibility, solid oxide fuel cells (SOFCs) have attracted particular attention from both the public and research community to create a more sustainable future [1–3]. The reduction of the operation temperature from the convention of approximately 1000 °C to the intermediate temperature range of 500–800 °C is critical to accelerating the commercialization of this fascinating technology because many drawbacks associated with high-temperature operation can be eliminated. However, a quick increase in polarization resistance with the drop in operation temperature is often observed for the conventional $\text{La}_{0.8}\text{Sr}_{0.2}\text{MnO}_3$ (LSM) cathode. This transition occurs due to the large activation energy associated with the oxygen reduction process (typically greater than 120 kJ mol^{-1}) and the small amount of active sites for oxygen reduction lim-

ited to the narrow region of electrolyte–electrode–air triple phase boundary (TPB) [4,5]. Currently, the cathode has become the major obstacle in realizing the lower temperature operation of SOFCs.

The cathode performance is closely related to its material composition. By applying mixed oxygen ionic and electronic conducting oxides as the electrodes, the active sites for oxygen reduction can potentially extend from the typical TPB region to the entire exposed cathode surface; this adjustment could lead to an enhanced activity for oxygen reduction at reduced temperatures. At present, considerable research efforts aim to develop innovative materials possessing both high surface activity and bulk oxygen ionic conductivity as cathodes of SOFCs [6–10]. Meanwhile, the electrode performance is intimately related to the electrode microstructure, which can influence both the gas diffusion and charge transfer processes.

In 2004, Shao et al. first reported the application of a perovskite-type $\text{Ba}_{0.5}\text{Sr}_{0.5}\text{Co}_{0.8}\text{Fe}_{0.2}\text{O}_{3-\delta}$ (BSCF) mixed conducting oxide as a cathode of intermediate-temperature (IT)-SOFCs on a thin-film samarium doped ceria (SDC) electrolyte [11]. BSCF shows an extraordinarily high oxygen vacancy concentration, which results in a high oxygen bulk diffusion rate and surface exchange kinetics, both of which are beneficial for the oxygen reduction reaction. The reports describe very low electrode area specific resistance

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Table 1
Summary of the peak power density (PPD) of the cell with BSCF cathode and/or the area specific resistance (ASR) of BSCF cathode at 600 °C.

Cell compositions	Electrolyte thickness (μm)	Atmosphere	Current collector	PPD (mW cm^{-2})	ASR (Ωcm^2)	Ref.
NiO + SDC SDC BSCF	20	3% H ₂ O humidified H ₂ /Air	Ag paste	1010	0.06	[11]
NiO + SDC SDC BSCF	20	3% H ₂ O humidified H ₂ /O ₂	unknown	840	–	[15]
NiO + SDC SDC BSCF	10	H ₂ /Air	unknown	1357	0.07	[18]
NiO + SDC SDC BSCF	12	H ₂ /Air	unknown	1080	0.08	[19]
Pt GDC BSCF	280	Moistened pure H ₂ /Air	Pt paste	~12	–	[20]
BSCF GDC BSCF*	1000	Air	Pt layer containing 15 wt% GDC powder	–	0.15	[21]
BSCF SDC BSCF*	800	Air	Ag paste	–	0.072	[22]
BSCF SDC BSCF*	1500	Air	Gold mesh	–	0.51	[23]
BSCF SDC BSCF*	800	Air	Ag paste	–	0.099	[24]
BSCF SDC BSCF*	500	Air	unknown	–	0.195	[25]
Ag paste SDC BSCF**	400	Air	Unknown	–	~3	[26]
Ag paste SDC BSCF**	unknown	Air	Ag paste	–	0.85	[27]

* Results were measured based on a two electrode configuration.

** Results were measured based on a three-electrode configuration.

(ASR) from symmetric cell tests and high cell power output for an anode-supported fuel cell with a thin-film SDC electrolyte (20 μm) and BSCF cathode. Inspired by the outstanding performance, many researchers have studied the properties and performance of BSCF, including its phase structure, oxygen nonstoichiometry, phase stability, and performance in a single cell [12–17]. However, as listed in Table 1 [11,15,18–27], large deviations in the values of cell power outputs and/or ASRs were demonstrated in literature, though their cell configuration and fabrication processes are similar. For example, Shao et al. reported a maximum peak power density of 1010 mW cm^{-2} at 600 °C for an anode-supported cell with a 20- μm thick SDC electrolyte and BSCF cathode, while Yan et al. obtained a value of only 840 mW cm^{-2} at the same temperature for similar cells [11,15]. Meanwhile, ASR values of 0.072 Ωcm^2 and 0.51 Ωcm^2 at 600 °C were reported by Zhou et al. and Deng et al., respectively, though both were based on a two-electrode configuration [22,23]. Such discrepancies are hardly explainable by the difference in electrode microstructures. Understanding the origin of such large differences is significant for further optimization of electrode performance and for practical application.

Because oxygen reduction processes involve electron transportation, the electrode is required to be electronically conductive. BSCF has relatively low electrical conductivity. A dense-type BSCF has a maximum conductivity value of only 40–50 S cm^{-1} in the intermediate temperature range (500–800 °C) in air, and this value is further reduced to only approximately 10 S cm^{-1} under a nitrogen atmosphere ($P_{\text{O}_2} \sim 10 - 5 \text{ atm}$) [28]. As a practical electrode of SOFCs, BSCF possesses a porosity of 20–50%, which may substantially reduce the apparent conductivity when compared to dense pellets. The electrical conductivity of a porous electrode could be at least one order of magnitude less than that of a dense pellet [29]. Although the current collector does not directly participate in the electrochemical process, inefficient current collection may introduce non-negligible contacting resistance and/or increase the charge transfer resistance noticeably, in particular under a large polarization current.

In this study, the effect of the current collection material and method on the performance of BSCF electrodes was systematically investigated. Ag paste and LaCoO₃ (LC) oxide were specifically selected as the current collectors, and five different current-collecting techniques were studied. Significantly different electrode performances were demonstrated by both symmetric cell and single cell tests, suggesting that the discrepancies in the electrode performance of BSCF in the literature are likely related to the current collection problem. Adopting the proper current collection material and method is crucial to achieve the high performance of BSCF cathodes.

2. Experimental

2.1. Powder synthesis

BSCF, LC and Sm_{0.2}Ce_{0.8}O_{1.9} (SDC) were all synthesized by an EDTA-citrate complexing process. The preparation of BSCF is given as an example. Ba(NO₃)₂, Sr(NO₃)₂, Co(NO₃)₂·yH₂O and Fe(NO₃)₃·yH₂O were used as the raw materials for metal sources. Co(NO₃)₂·yH₂O and Fe(NO₃)₃·yH₂O were first dissolved in de-ionized water to prepare aqueous solutions, and their precise concentrations were determined by an EDTA titration method. The detailed procedure can refer to our published paper [10,22]. The final calcination temperatures of BSCF, LC and SDC were 900, 950 and 800 °C, respectively.

2.2. Fabrication of symmetric and anode-supported cells

The as-synthesized SDC powder was ball milled to reduce the amount of soft aggregates and fabricated into disk-shape pellets by dry pressing. Those green SDC pellets were sintered at 1400 °C for 5 h in air. The sintered SDC pellets with a diameter of approximately 13 mm were polished by an attrition paper to a thickness of 0.9 mm. A BSCF slurry, prepared by ball milling BSCF powder in a premixed solution of glycerol, isopropyl alcohol and ethylene glycol, was then deposited onto both surfaces of the SDC pellets by a spray deposition technique. The resulting cells were fired at 1000 °C for 2 h in air to obtain symmetrical cells with the configuration of BSCF|SDC|BSCF for impedance measurement.

The fuel cells applied in this study were in the anode-supported, thin-film electrolyte configuration. Two types of fuel cells were fabricated: (1) NiO + SDC anode-supported fuel cell with SDC electrolyte and (2) NiO + YSZ|YSZ|SDC anode-supported fuel cell with YSZ and SDC dual-layer electrolyte. The NiO + SDC|SDC dual layer pellets were fabricated by a dry pressing and co-sintering technique. The detailed fabrication process was described previously [30]. The NiO + YSZ anode substrates were prepared by tape casting and punched into disk-shaped anode substrates with diameters of 16 mm, and then they were sintered at 1150 °C in air to remove organic materials. The YSZ electrolyte layer was prepared via wet powder spraying and sintering. The spraying process was carried out at 200 °C by heating the anode substrates over a hot paste. The obtained NiO + YSZ|YSZ green disks were sintered at 1400 °C for 5 h in air. After sintering, the disks have a diameter of approximately 13 mm. Then the SDC thin-film electrolyte layer was prepared by the same wet powder spraying technique and sintered at 1350 °C for 5 h, resulting in anode-supported, YSZ|SDC dual-layer electrolyte pellets. Finally, the BSCF slurry was deposited on the central surface of the two types of anode-supported SDC electrolytes by spray deposition, and the device was

fired at 1000 °C for 2 h. The cathode has a geometric surface area of 0.48 cm².

2.3. Current collection

Ag paste and LC oxide were studied as current collectors. All together, five different current collection techniques were investigated, including two different current collection methods for the Ag paste and two different techniques for LC oxide, as shown in Fig. 1. In some studies, a silver wire was directly fixed to the central surface of the BSCF electrode by Ag paste; as the area of the Ag paste is very small (approximately 0.02 cm²) compared to the geometric surface area of BSCF (0.48 cm²), the resulting devices can be viewed as having no current collector applied (technique 1). To use Ag as a current collector, a dense Ag paste was applied to the material, which contained >80 wt.% silver powder that is balanced by organic additives. Two methods of the current collection were studied; the undiluted Ag paste was directly applied to the entire surface of BSCF electrode by painting (technique 2), or it was first diluted with ethanol with polyvinyl butyral (PVB) before applying it to the BSCF surface (technique 3). To apply LC as the current collector, it was deposited onto the BSCF electrode surface by painting and fired at 950 °C for 5 h to allow firm adhesion between LC and the BSCF layer while effectively suppressing the phase reaction between LC and BSCF [22] (technique 4). Also, the LC current collector surface was further modified with a layer of diluted Ag paste (technique 5). For techniques 2 through 5, silver wires were attached to the central electrode surface by Ag paste with a dot.

2.4. Electrochemical characterization

The single cell test was conducted over an in-lab constructed fuel cell test station. During the measurement, H₂ was fed into the anode side as fuel at a flow rate of 80 ml min⁻¹ [STP], while ambi-

ent air was the cathode atmosphere. *I*–*V* polarization curves were collected by a digital electrometer (Model 2420, Keithley, USA) in four-probe mode. The electrochemical impedance spectra (EIS) of the single cells or symmetric cells were measured using an electrochemical workstation based on a Solartron 1260A frequency response analyzer and a Solartron 1287 Potentionstat/Galvanostat under open air circuit (OCV) conditions. The frequency range was 0.1 Hz to 1 MHz, and the signal amplitude was 10 mV.

2.5. Other characterizations

The electrical conductivity of BSCF and LC was measured by a four-probe DC conductivity technique. Approximately 1 g BSCF and LC powders were pressed into bars and sintered at 1100 °C for 5 h. Undiluted Ag paste was painted on the square cross-sectional edges and two circumferential surfaces of the bar to form the current and voltage electrodes. Two silver wires acting as current contacts and two silver wires acting as voltage contacts were attached to the electrodes. The current was applied to the two current wires, and the voltage was detected by the digital electrometer (Model 2420, Keithley, USA) from 900 to 300 °C at intervals of 10 °C in air.

The surface conductivity of the porous BSCF cathode, LC current collector and Ag paste collector was also tested using the same four-probe DC conductivity technique, as described above. Details can be found in literatures [31,32]. In this experiment, the BSCF or LC slurries were sprayed onto SDC electrolytes and fired at 1000 and 950 °C for 2 h, respectively. The diluted Ag paste was applied onto the SDC electrolyte with a brush, and the device was fired at 700 °C for 2 h. The electrical contact for the current and voltage probes was made with very small amounts of undiluted Ag paste. Measurements were carried out in air in the temperature range of 450 and 700 °C.

The surface and cross-sectional morphologies of the symmetric cells were observed by an environmental scanning electron microscope (ESEM, QUANTA-200).

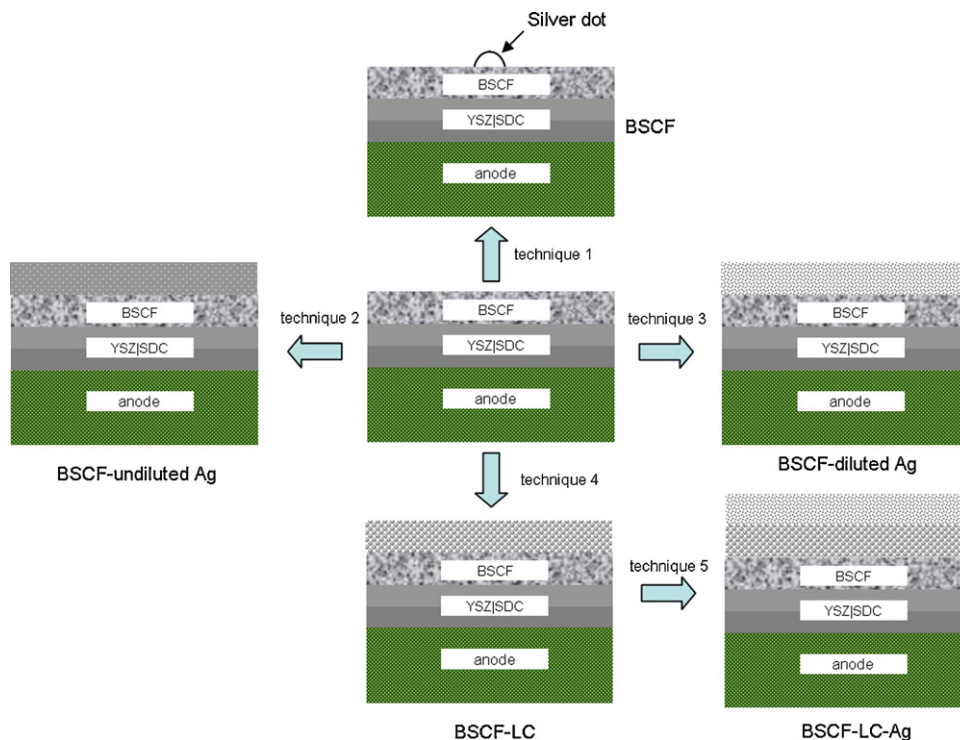


Fig. 1. A schematic diagram of the fabrication of NiO + YSZ|YSZ|SDC anode-supported fuel cells with different current collection materials and techniques.

3. Results

3.1. Single cell performance

The current collector is an important component of the fuel cell system that collects the current from the anode or distributes the current homogeneously over the cathode. A potential material for current collectors should satisfy a number of different criteria, including good electrical conductivity, high thermal/chemical stability under operational conditions and low fabrication costs [33]. Silver, which has been often applied as the current collector for IT-SOFCs in lab investigation, has very high electrical conductivity ($6.2 \times 10^5 \text{ S cm}^{-1}$ at room temperature); however, the long-term stability of silver may be still questionable. At the same time, some composite oxides with high electrical conductivities, such as $\text{LaNi}_{0.6}\text{Fe}_{0.4}\text{O}_3$ and $\text{La}_{0.8}\text{Sr}_{0.2}\text{MnO}_3$, are also applied as current collectors [34,35]. Zhou et al. have demonstrated that

LaCoO_3 perovskite oxide has high electrical conductivity (approximately 700 S cm^{-1}) at elevated temperatures in air [22]. Thus, Ag paste and LC were tried as the current collectors in this study. The effect of current collection methods on the single cell performance was first investigated. Two types of fuel cells are investigated: the NiO+SDC anode-supported thin-film SDC electrolyte fuel cell and the NiO+YSZ anode-supported thin-film electrolyte fuel cell with a YSZ and SDC dual-layer electrolyte fuel cell.

Fig. 2 presents I - V and I - P curves of the various anode-supported dual-layer electrolyte fuel cells with the same BSCF cathode and different current collection methods between 550 and 750 °C. All of the cells showed high open circuit voltages (OCVs), which are close to the predicted values from the Nernst equation, suggesting that the YSZ/SDC dual-layer electrolyte is dense and gas-tight. A significant impact of the current collection methods on the cell performance was clearly demonstrated from the results in Fig. 2. For

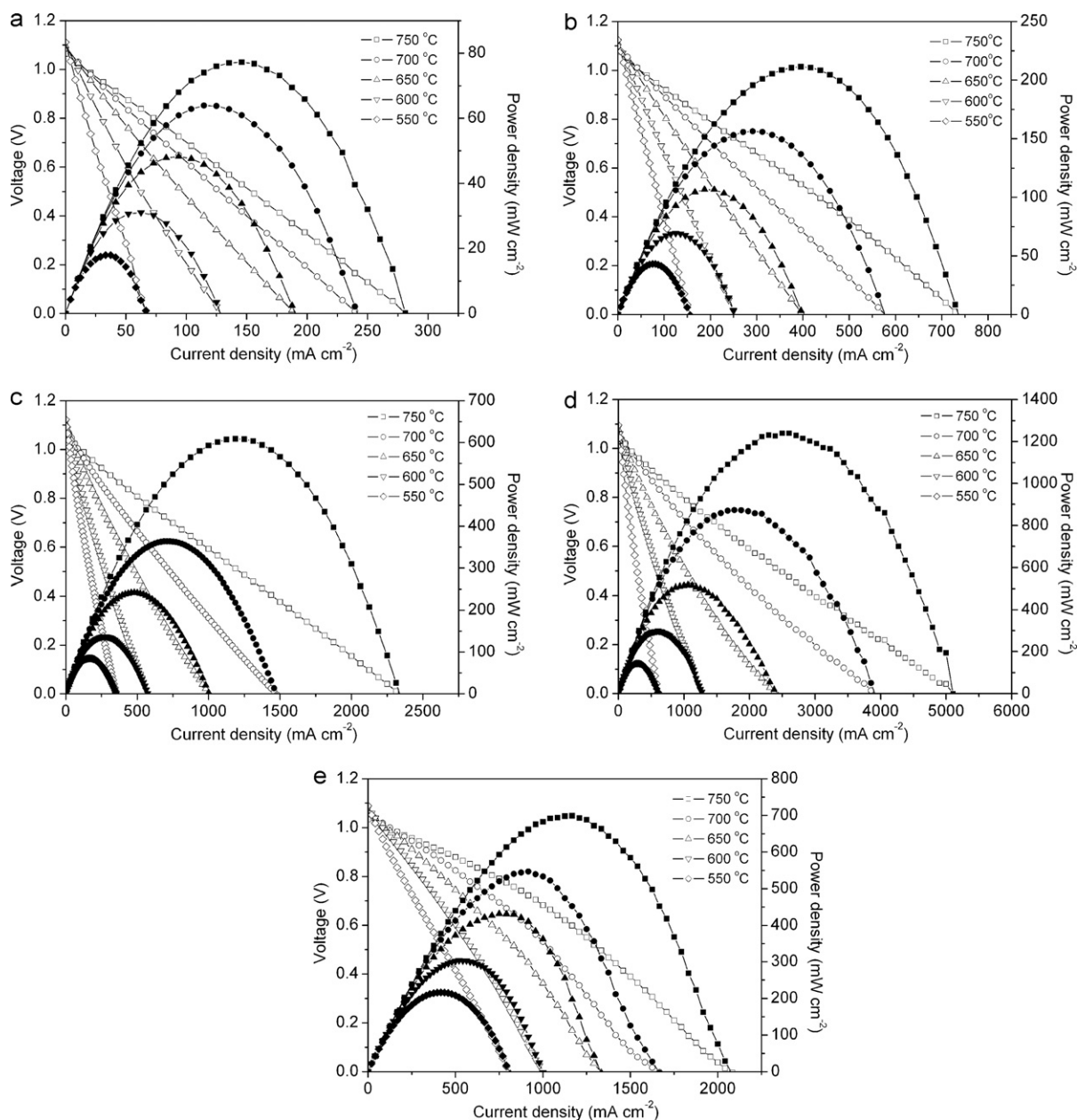


Fig. 2. The I - V and I - P curves of the NiO+YSZ/YSZ/SDC/BSCF fuel cells with various current collectors at 550–750 °C: (a) without a current collector; (b) LC; (c) LC-Ag; (d) diluted Ag paste; (e) undiluted Ag paste.

Table 2

Comparison of the open circuit voltage (OCV) and peak power density (PPD) of cells on thin-film SDC electrolyte with different current collectors at 600 °C.

Current collector	No current collector	LC	LC-Ag	Undiluted Ag paste	Diluted Ag paste
OCV (V)	0.82	0.81	0.81	0.81	0.82
PPD (mW cm^{-2})	30	227	546	697	960

the cell without a current collector (technique 1), the peak power densities were only 77, 63, 48 and 31 mW cm^{-2} at 750, 700, 650 and 600 °C, respectively. By applying LC as the current collector (technique 4), the cell performance significantly improved, and the peak power densities reached 211, 156, 106 and 69 mW cm^{-2} at 750, 700, 650 and 600 °C, respectively. A further improvement in cell performance was demonstrated by adopting an LC-Ag current collector (technique 5), and the cell delivered peak power densities of 608, 363, 242 and 137 mW cm^{-2} at 750, 700, 650 and 600 °C, respectively. The maximum power densities of 1240, 873, 517 and 299 mW cm^{-2} were obtained at 750, 700, 650 and 600 °C, respectively, for the cell with diluted Ag paste as the current collector (technique 3). By applying undiluted Ag paste as the current collector (technique 2), the peak power densities are 698, 546, 431 and 283 at 750, 700, 650 and 600 °C, respectively. The noticeable difference in peak power densities of the cells with Ag paste as the current collectors (techniques 2 and 3) indicate that the cell performance is also influenced by the method of current collection. In this study, the maximum difference of peak power density among the cells with different current collection method is as large as factors of 16 and 10 at 750 and 600 °C, respectively.

The significant effects of the current collection material and technique on the cell performance were also demonstrated for the cell with a single layer SDC electrolyte. Table 2 lists the peak power densities of the various anode-supported thin-film SDC electrolyte fuel cells with the same BSCF cathode and different current collection methods at 600 °C. At 600 °C, the cell with diluted Ag paste, undiluted Ag paste, LC-Ag, LC and no current collector have peak power densities of 960, 697, 546, 227 and 30 mW cm^{-2} , respectively. Because the cells were fabricated and tested under the same conditions, the large variations in performance are mainly related to their different current collection materials or methods.

The cell performance is influenced by the cell ohmic resistance and the electrode polarization resistance [36]. Fig. 3 shows the

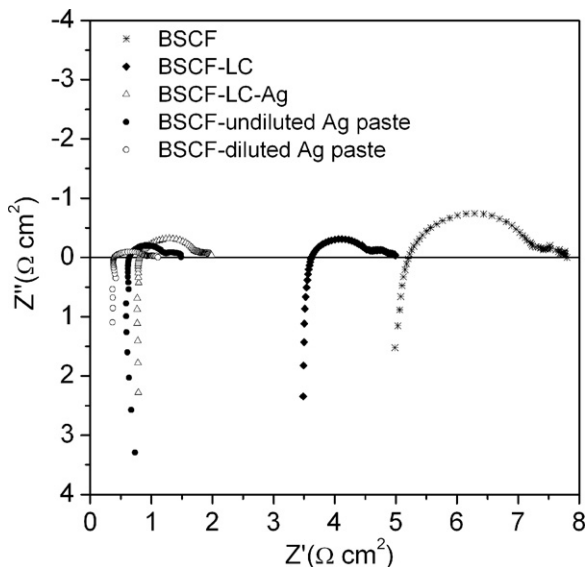


Fig. 3. EIS of the NiO + YSZ|YSZ|SDC|BSCF cells with various current collectors at 600 °C under OCV conditions.

EIS in Nyquist plots of the NiO + YSZ|YSZ|SDC|BSCF cells with different types of current collectors under open circuit conditions at 600 °C. The cell resistance was significantly affected by the current collection material and also by the current collection technique. The cell with the diluted Ag paste shows the lowest ohmic and polarization resistances when compared to the other cells; the cell without a current collector shows the highest ohmic and polarization resistances. The cell with the LC-Ag paste has a lower ohmic and polarization resistance relative to the cells with LC or nothing as the current collector; however, its ohmic resistance and electrode polarization resistance are higher than those of the cells with diluted or undiluted Ag paste. The cell ohmic resistance contains the electrical resistances of the electrodes and the electrolyte, the contact resistance between the lead wire and the electrode, and the resistance of the lead wire [37]. Clearly, the difference in ohmic resistance for the different cells is mainly attributed to the contact resistance because there is no difference in the electrolyte, electrode or lead wires of the various cells. The electrode polarization resistance in the single cell is the sum of the anodic and cathodic polarization resistances. The fact that the anode is identical for the various cells suggests that the current collectors have strong effects on the BSCF cathode performance.

3.2. EIS

To further illustrate the effects of different current collectors (method and material) on the electrochemical performance of the BSCF cathode, symmetrical cells with a BSCF cathode and various current collectors were fabricated and tested. Fig. 4 presents the Nyquist plots of the symmetrical cells with different types of cathode current collectors at an operating temperature of 600 °C. The measured results of total resistance (R_{total}), ohmic resistance (R_{ohmic}) and electrode polarization resistance (R_p) are listed in Table 3. Large differences are present in both R_{ohmic} and R_{total} by applying the different current collection materials and current collection techniques. R_{total} , R_{ohmic} and R_p decreased in the sequence of silver dot, LC, LC-Ag, undiluted Ag paste and diluted Ag paste. The ohmic resistance of the cell with only the silver dot to fix the silver wire, which reaches as high as 23.3 $\Omega \text{ cm}^2$, is the highest. The cell with the LC current collector has an ohmic resistance of 12.7 $\Omega \text{ cm}^2$, which is only half of that of the cell with the silver dot. The ohmic resistance of the cell decreases to 2.3 $\Omega \text{ cm}^2$ when the LC-Ag is applied as the current collector. Notably, the ohmic resistance of the cell with diluted Ag paste is reduced to only 1.4 $\Omega \text{ cm}^2$, while this value is 1.7 $\Omega \text{ cm}^2$ when applying undiluted Ag paste as the current collector. As no differences in the electrolyte thickness are present, the ohmic resistance depends greatly on the contact resistance between the current collector and the cathode. These results

Table 3

Area specific resistance of the symmetrical cells with different types of current collector at 600 °C.

Current collector	Area specific resistance ($\Omega \text{ cm}^2$)		
	R_{total}	R_{ohmic}	R_p
Without current collector	23.9	23.3	0.7
LC	12.9	12.7	0.3
LC-Ag	2.6	2.3	0.2
Undiluted silver paste	1.9	1.7	0.2
Diluted silver paste	1.5	1.4	0.1

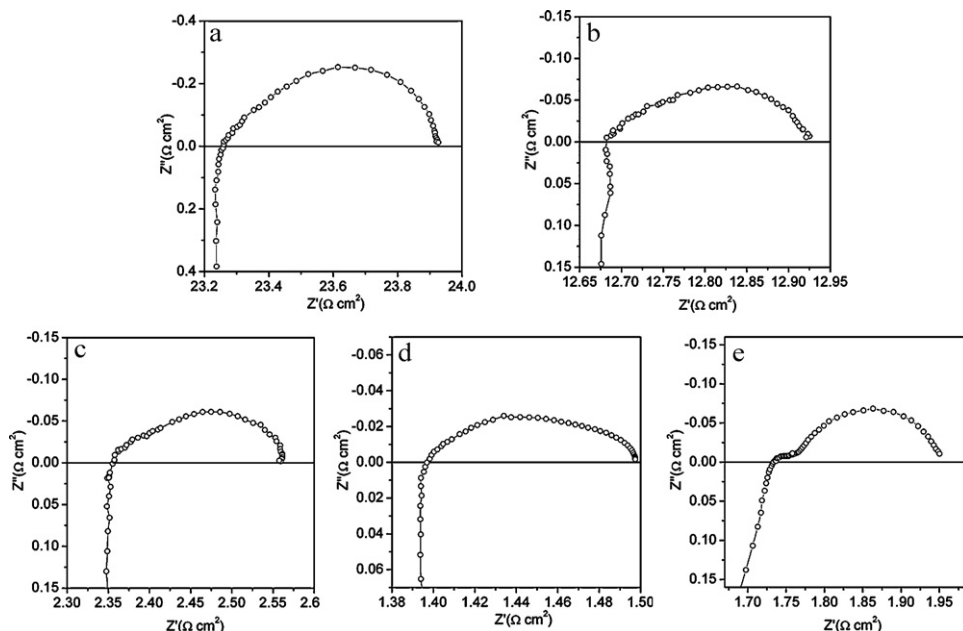


Fig. 4. Nyquist plots of EIS for symmetrical cells with BSCF electrodes and various current collectors at 600 °C: (a) without a current collector; (b) LC; (c) LC-Ag; (d) diluted Ag paste; (e) undiluted Ag paste.

indicate that using a proper current collector can lower the ohmic resistance of the cell, particularly the contact resistance between the cathode and the current collector. The cell with a silver dot shows the highest electrode polarization resistance ($0.7 \Omega \text{ cm}^2$), and the cell with LC, LC-Ag and diluted Ag paste current collectors

have electrode polarization resistances of 0.3, 0.2 and $0.1 \Omega \text{ cm}^2$, respectively. The distinct behaviors of R_{ohmic} and R_p can be related to the different current collectors, suggesting that the current collectors not only affect the ohmic resistance of the cells but also the BSCF cathode polarization resistance.

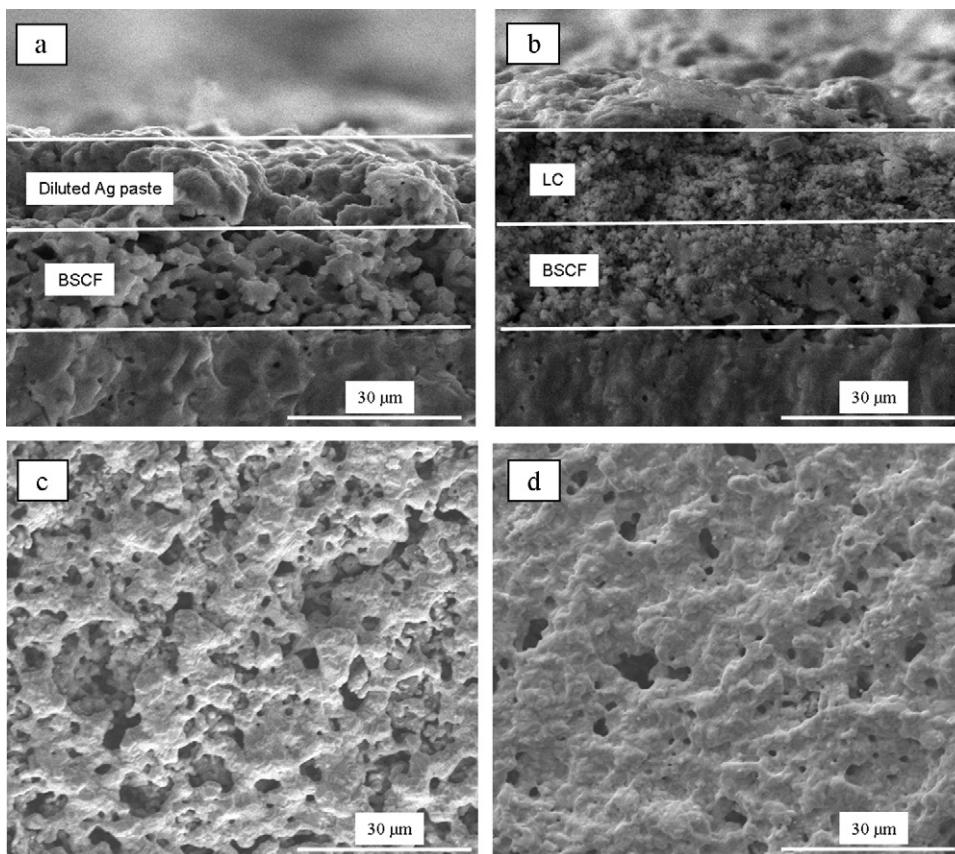


Fig. 5. The SEM images of the symmetrical cells with BSCF electrodes and various current collectors: (a) diluted Ag paste; (b) LC-Ag; (c) surface of diluted Ag paste; (d) surface of undiluted Ag paste.

3.3. Electrode morphology

From EIS, the current collectors clearly have significant effects on the contact resistance and the electrode polarization resistance. To exploit the origin of such effects, the morphologies of the current collectors and the electrode were observed by SEM. Fig. 5 shows the surface and cross-sectional micrographs of the symmetrical cells with different current collectors. As shown in Fig. 5a and b, the BSCF electrodes have similar highly porous structures, and the thicknesses of all of the cells are approximately 20 μm . The porous BSCF cathode shows good adhesion to the dense SDC pellet and has a homogeneous microstructure with well-contacted particles. This observation suggests that the differences in electrode and cell performance with different current collectors, as demonstrated in Sections 3.1 and 3.2, are not likely due to the microstructure and thickness of BSCF cathode. The LC current collector was more porous with a thickness of 17 μm , and the particle size of LC is smaller than that of BSCF. As shown in Fig. 5c and d, the Ag current collector prepared with undiluted Ag paste is much less porous than that prepared by the diluted Ag paste.

3.4. Surface conductivity

High electrical conductivity is important for the efficient current collection and the decrease of contact resistance between the current collector and electrode [33,38]. Therefore, in this study, we first measured the electrical conductivity of LC, which will be used as a current collector for the BSCF cathode. The values of the dense LC sample for the temperature from 300 to 900 $^{\circ}\text{C}$ are shown in Fig. 6; for comparison, the electrical conductivity of BSCF and the reported value of LC are also given. The electrical conductivity of LC oxide increases with temperature up to a maximum and then decreases with increasing temperature; these results agree well with our previous study by Zhou et al. [22]. For the BSCF sample, the electrical conductivity first increases linearly with temperature until 510 $^{\circ}\text{C}$; above this temperature, this value remains almost constant with

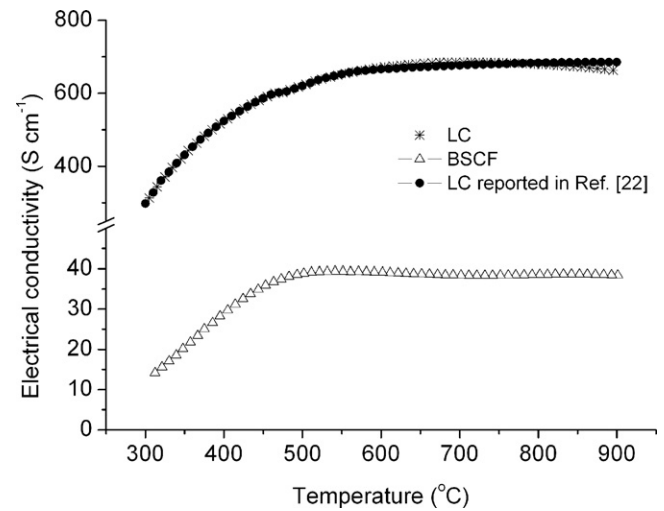


Fig. 6. The time dependence of the electrical conductivities of BSCF and LC oxides.

respect to further increases in temperature. The conductivities of BSCF are much lower than those of LC in the temperature range of 300–900 $^{\circ}\text{C}$. At 800 $^{\circ}\text{C}$, for example, the conductivities of BSCF and LC are 31.6 and 679.5 S cm^{-1} , respectively; the electrical conductivity of LC is more than twenty times greater than that of BSCF at 800 $^{\circ}\text{C}$. The results showed that LC has enough electrical conductivity to be applied as a current collector of a BSCF cathode.

Although LC has very high electrical conductivity in a dense pellet, the electrode performance of the BSCF cathode with LC was worse than that of cells with diluted or undiluted Ag paste. As we know, the current collector layer should have enough porosity for gas diffusion; the electrical conductivity of LC will decrease with increasing porosity. To collect the current of the BSCF cathode effectively, the current collector should also have enough surface conductivity. Here we further investigated the surface conductivity

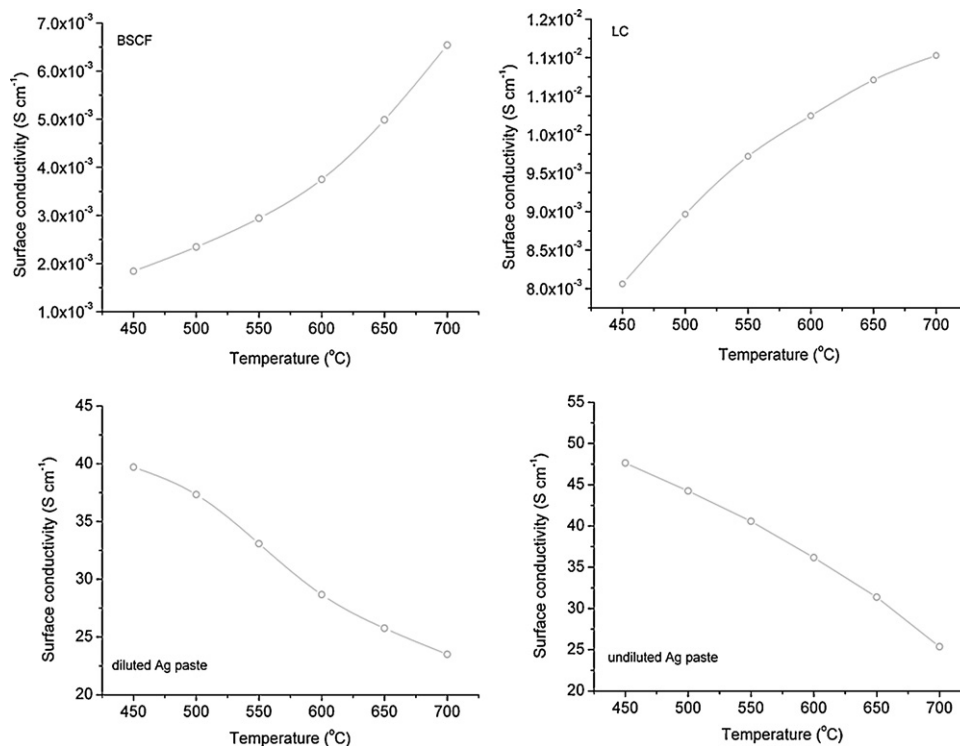


Fig. 7. The surface conductivities of the various current collectors at 450–700 $^{\circ}\text{C}$: (a) BSCF; (b) LC; (c) diluted Ag paste; (d) undiluted Ag paste.

ity of BSCF, LC, and diluted and undiluted Ag paste in the range of 450–700 °C, and the values are shown in Fig. 7. The surface conductivities of BSCF and LC increase with temperature, and the values are 6.5×10^{-3} and $1.1 \times 10^{-2} \text{ S cm}^{-1}$ at 700 °C, respectively. The surface conductivity of LC is only two times greater than that of BSCF, although the electrical conductivity of LC is twenty times that of BSCF at 700 °C (shown in Fig. 6). As shown in Fig. 7c and d, the surface conductivity of Ag paste (diluted and undiluted) generally decreases with temperature, and the values of undiluted Ag paste are greater than that of diluted Ag paste at corresponding temperatures. The surface conductivity of undiluted and diluted Ag paste can reach 25.4 and 23.5 S cm^{-1} at 700 °C, respectively, which indicates that the surface conductivity is also affected by the porosity of material. Meanwhile, the value of Ag paste is two thousand times greater than that of LC or BSCF.

4. Discussion

The choice of a proper current collector in an electrode has been identified as an important component, especially for the practical application of SOFCs due to the fact that an inadequate current collector will lead to large voltage losses in the SOFCs stack. In connection with the results in Fig. 2, Fig. 3 and Table 2, current collection material and method could significantly affect the ohmic and polarization resistances of the cells, thus, the outputs of single cells. Since the cells with different current collectors have the same anode, electrolyte and cathode, the difference in resistances may be affected by the current collectors. Therefore, symmetrical cells with BSCF cathodes and different current collectors were used to identify the origins of the effect of the current collection material and technique on the cell performance. As expected, shown in Fig. 4 and Table 3, the R_{total} , R_{ohmic} and R_p decreased, in the sequence, by applying LC, LC-Ag, undiluted Ag paste and diluted Ag paste as the current collector, and the decrease of R_{ohmic} is dominant in R_{total} . This observation indicated that the current collector affected not only the BSCF cathode polarization resistance but also the ohmic resistance of the cell.

Usually, the oxygen-reduction reaction over the electrodes is regarded as a combination of charge-transfer processes and diffusion processes. The diffusion processes involve the adsorption and desorption of oxygen, oxygen diffusion at the gas–cathode interface and the surface diffusion of intermediate oxygen species. The charge-transfer processes include both electron transfer and ion transfer processes, which occur at the current collector/electrode and electrode/electrolyte interfaces [39]. Because all of the symmetrical cells with different current collectors have the same BSCF electrode material and similar electrode microstructures and thicknesses (shown in Fig. 5), the variation in R_p is less likely to originate in the diffusion processes. Different current collection materials and methods likely result in different electron transfer processes occurring at the current collector/electrode interface and, thus, different R_p values. At the same time, the R_p of the cell with undiluted Ag paste as current collector is still much higher than that of the cell with diluted Ag paste as current collector. The gas diffusion polarization resistance is likely non-negligible for the insufficient porosity of the diluted Ag paste current collector. This hypothesis may explain the differences in cell performances reported by different researchers [11,15], though they applied similar cells with BSCF cathodes and Ag pastes as the current collectors.

The ohmic resistance primarily includes the electrolyte resistance, electrode ohmic resistance and contact resistances at the cathode/electrolyte and cathode/current collector interfaces. As shown in Fig. 5, the difference in ohmic resistance is less affected by the electrolyte resistance, electrode ohmic resistance, microstructure and thickness. Thus, assumedly, the decrease of ohmic

resistance of the cell with diluted Ag paste is mainly due to the improved BSCF cathode/current collector interface.

As can be seen from Fig. 6, the electrical conductivity of dense LC is quite high, and the value at 800 °C can reach 679.5 S cm^{-1} , which is more than twenty times greater than that of BSCF. However, as shown in Fig. 7, the surface conductivities of BSCF and LC were still low, and the values are only 6.5×10^{-3} and $1.1 \times 10^{-2} \text{ S cm}^{-1}$, respectively, at 700 °C. The poor surface conductivity of the LC current collector may be ascribed to poor sintering that resulted from the relatively low firing temperature in this study. The surface conductivity of diluted Ag paste is 2–3 orders of magnitude higher than that of LC or BSCF, for example, the surface conductivity of diluted Ag paste can reach 23.5 S cm^{-1} at 700 °C. As mentioned, the increased surface conductivity of the current collector can lower the ohmic resistances of the current collector and at the BSCF/current collector interface.

5. Conclusions

From this study, the electrochemical performance of anode-supported SOFCs with BSCF cathodes was highly sensitive to the current collection material and method. We believed the large differences in the literature results about BSCF electrodes are, at least in part, due to the different current collection materials and/or techniques. The current collector affected not only the polarization resistance of BSCF but also the ohmic resistance of the cells. Although LC is a good electronic conductor in a dense form, its surface conductivity is still low in a porous state fired at 950 °C; thus, LC is not an ideal current collector for BSCF. The surface conductivity of undiluted or diluted Ag paste is more than 2000 times greater than that of LC or BSCF, which enhanced the contact at the cathode/current collector interface. However, the improper fabrication of Ag current collectors could create insufficient porosity, which increases the electrode polarization resistance. To achieve high cell performance, the choice of a proper current material and method is highly crucial because these properties help to lower the ohmic resistance of the cell, particularly the contact resistance between the cathode and the current collector.

Acknowledgements

This work was supported by the “National Science Foundation for Distinguished Young Scholars of China” under contract no. 51025209, by “Outstanding Young Scholar Grant at Jiangsu Province” under contract no. 2008023, by program for New Century Excellent Talents (2008), and by Fok Ying Tung Education Foundation under contract no. 111073.

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