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Study of transition metal oxide doped LaGaO$_3$ as electrode materials for LSGM-based solid oxide fuel cells

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Abstract Transition metal oxide doped lanthanum gallates, La$_{0.9}$Sr$_{0.1}$Ga$_{0.8}$M$_{0.2}$O$_3$ (where M = Co, Mn, Cr, Fe, or V), are studied as mixed ionic-electronic conductors (MIECs) for electrode applications. The electrochemical properties of these materials in air and in H$_2$ are characterized using impedance spectroscopy, open cell voltage measurement, and gas permeation measurement. Three single cells based on La$_{0.9}$Sr$_{0.1}$Ga$_{0.8}$Mg$_{0.2}$O$_3$ (LSGM) electrolyte (1.13 to 1.65 mm thick) but with different electrode materials are studied under identical conditions to characterize the effectiveness of the lanthanum gallate-based MIECs for electrode applications. At 800 °C, a single cell using La$_{0.9}$Sr$_{0.1}$Ga$_{0.8}$Co$_{0.2}$O$_3$ as the cathode and La$_{0.9}$Sr$_{0.1}$Ga$_{0.8}$Mn$_{0.2}$O$_3$ as the anode shows a maximum power density of 88 mW/cm$^2$, which is better than that of a cell using Pt as both electrodes (20 mW/cm$^2$) and that of a cell using La$_{0.9}$Sr$_{0.1}$CoO$_3$ (LSC) as the cathode and CeO$_2$-Ni as the anode (61 mW/cm$^2$) under identical conditions. The performance of LSGM-based fuel cells with MIEC electrodes may be further improved by reducing the electrolyte thickness and by optimizing the microstructures of the electrodes through processing.

Key words Lanthanum gallate · Mixed ionic-electronic conductor · Electrode materials · Solid oxide fuel cells

Introduction

Because of their excellent oxide-ion conductivity and stability over a broad range of oxygen partial pressures, LaGaO$_3$-based electrolytes such as La$_{0.9}$Sr$_{0.1}$Ga$_{0.8}$Mg$_{0.2}$O$_3$ (LSGM) are considered to be a promising alternative to replace yttria-stabilized zirconia (YSZ) currently used in intermediate-temperature (600–800 °C) solid oxide fuel cells (SOFCs) [1–4]. The overall performance of an SOFC is determined by the electrochemical characteristics of each cell component, including the electrolyte, the cathode, the anode, and the interfaces between cell components. Accordingly, once a new electrolyte is identified, the development of appropriate cathode and anode materials compatible with the electrolyte becomes critical to the successful development of a new fuel cell system. Compared to high-temperature SOFCs based on YSZ electrolytes, the performance of intermediate-temperature SOFCs depends more on the electrode-electrolyte interfaces, since the interfacial polarization of a solid-state cell increases rapidly as the operating temperature is reduced [5].

The electrodes for SOFCs should have high electrical conductivity, high catalytic activities, adequate porosity for gas transport, and sufficient stability in contact with other cell components (electrolyte, interconnect, and current collector) under processing and operating conditions. Oxidation of oxygen at a cathode may involve the following steps: chemisorbing oxygen, reducing the chemisorbed oxygen to oxygen ions, and delivering the oxygen ions from the reaction sites to the electrolyte. If the cathode is a pure electronic conductor, oxygen reduction must take place at the triple-phase boundaries (TPBs) between gaseous O$_2$, the cathode, and the electrolyte. Traditionally, relatively thick and porous electrode/electrolyte composite films are employed to increase the number of TPB reaction sites; however, this also inevitably creates an additional tortuous pathway through which both ionic and electronic defects must travel. If the electrode is made of a mixed ionic-elec-
tronic conductor (MIEC), however, the reaction sites will be extended beyond the TPBs to the MIEC/gas interface [6]. When the ionic and electronic conductivities of the MIEC electrode are sufficiently high, electrode reactions may occur over the entire MIEC/gas interface, significantly increasing the number of reaction sites compared to electrodes of pure electronic conductors. Further, MIECs may exhibit higher catalytic activity because of the ability of transporting both ionic and electronic defects.

The perovskites La$_{1-x}$Sr$_x$MnO$_3$ (LSM) and La$_{1-x}$Sr$_x$CoO$_3$ (LSC) have been studied as cathode materials for LSGM-based SOFCs [7, 8]. While LSM is compatible with LSGM both chemically (insignificant interdiffusion) and thermally (similar thermal expansion coefficient), LSC is not suitable for the application owing to its considerable chemical interactions with LSGM and large mismatch in thermal expansion between LSC and LSGM. Owing to its limited ionic conductivity, however, LSM does not have adequate ambipolar conductivity to extend the reaction sites far beyond the TPBs [9]. Thus, MIECs with high ambipolar conductivities are needed to enhance the performance of the cathode. Similar to YSZ-based SOFCs, Ni-LSGM composite has been studied as the anode for LSGM-based SOFCs [8, 7]. Powder with stoichiometric composition were ball-milled in ethanol for 24 h and calcined at 1300 °C in air for 6 h to form the perovskite phase. X-ray powder diffraction (Philips, PW 1800) was used to monitor the phase composition of the calcined product. In cases of incomplete calcination, ball-milling and calcination were repeated until a pure perovskite phase was obtained. Powders with the perovskite phase were crushed using an agate mortar and pestle and then ball-milled in ethanol for 24 h. The resulting fine powders were pressed in pellets (diameter 20 mm and thickness 2–3 mm) and sintered at 1450 °C for 10 h. The densities of the sintered pellets were measured using the water-displacement technique. The sintered samples were polished, thermally etched, and then characterized using a scanning electron microscope (Hitachi S-800 SEM) to reveal the microstructures of the sintered samples.

**Determination of total conductivity in a uniform atmosphere**

Both surfaces of each sintered pellet were polished and ultrasonically cleaned before a paste of an Ag or Pt electrode was screen-printed on them. Pellets with printed electrodes were then fired at appropriate temperatures to form porous Ag or Pt electrodes. A computerized impedance analysis system, consisting of a Frequency Response Analyzer (Solartron 1255) and an Electrochemical Interface (Solartron 1286), was used to measure the impedance of the cells in the frequency range from 10 MHz to 1 MHz at temperatures ranging from 500 to 800 °C in air or H$_2$.

**Experimental**

Sample preparation

La$_2$(CO$_3$)$_3$·xH$_2$O, Ga$_2$O$_3$, SrCO$_3$, and MgO were used as precursors for the preparation of L$_{0.6}$Sr$_{0.4}$Ga$_{0.8}$Mg$_{0.2}$O$_3$, while CoCO$_3$·xH$_2$O, MnCO$_3$, FeC$_2$O$_4$, Cr$_2$O$_3$, and V$_2$O$_5$ were used as sources of transition metal ions to form transition metal doped LaGaO$_3$ with an intended formula of L$_{0.6}$Sr$_{0.4}$Ga$_{0.8}$M$_{0.2}$O$_3$, where M represents Co, Mn, Fe, Cr, or V. Powders with stoichiometric composition were ball-milled in ethanol for 24 h and calcined at 1300 °C in air for 6 h to form the perovskite phase. X-ray powder diffraction (Philips, PW 1800) was used to monitor the phase composition of the calcined product. In cases of incomplete calcination, ball-milling and calcination were repeated until a pure perovskite phase was obtained. Powders with the perovskite phase were crushed using an agate mortar and pestle and then ball-milled in ethanol for 24 h. The resulting fine powders were pressed in pellets (diameter 20 mm and thickness 2–3 mm) and sintered at 1450 °C for 10 h. The densities of the sintered pellets were measured using the water-displacement technique. The sintered samples were polished, thermally etched, and then characterized using a scanning electron microscope (Hitachi S-800 SEM) to reveal the microstructures of the sintered samples.

**Characterization of ionic and electronic conductivity using a concentration cell**

The ionic and electronic transference numbers were determined using the combination of impedance spectroscopy, open cell voltage measurement, and oxygen gas permeation measurement. Shown in Fig. 1 is a schematic arrangement for these measurements. Cells with Ag electrodes were attached to an alumina tube using a glass seal [10]. The glasses were fired in situ and the heating and cooling rates were carefully controlled to avoid cracking of the glass seal. The furnace was heated at 7 °C/min to 820 °C, held at that temperature for 10 min to soften the glass, and then cooled at 3 °C/min to the desired temperature for testing. Impedance spectra, open cell voltages, and oxygen permeation rates were measured under identical conditions on an oxygen concentration cell of air, Ag/La$_{0.6}$Sr$_{0.4}$Ga$_{0.8}$M$_{0.2}$O$_3$ (M = Mg, Co, or Mn)/Ag, Ar.

The oxygen concentration of the incoming and outgoing gas was monitored using a YSZ oxygen sensor.

**Fuel cell testing**

Three kinds of fuel cells (named as cell 1, cell 2, and cell 3) using the LSGM electrolyte were tested. In cell 1, Pt was used as both cathode and anode (fired at 1000 °C for 2 h). In cell 2, La$_{0.6}$Sr$_{0.4}$CoO$_3$ was used as the cathode material and CeO$_2$-Ni was used as the anode material. The anode was prepared through in situ reduction of CeO$_2$/NiO composite [8] in order to form porous CeO$_2$ with metallic Ni particles on the walls of the porous channels. In cell 3, La$_{0.6}$Sr$_{0.4}$Ga$_{0.8}$M$_{0.2}$O$_3$ was used as the cathode material and...
La$_{0.9}$Sr$_{0.1}$Ga$_{0.8}$Mn$_{0.2}$O$_3$ was used as the anode material. A slurry of each electrode material was obtained by mixing and grinding the powders with organic binder (Heraeus V-006) using a mortar and pestle. The electrode slurries were painted on the parallel surfaces of the LSGM pellet using a brush and then fired at 1100°C for 2 h. A thin porous platinum layer was applied on the top of both electrodes to act as a current collector.

The configuration of the fuel cell is similar to that of the oxygen concentration cell shown in Fig. 1. After the glass seals were fired in situ, argon was supplied to the anode while the cathode was exposed to ambient air. Approximately 30 min after the cell reached the operating temperature, the anode gas was switched to hydrogen containing 2% water vapor (hydrogen passing through water bubbler at $20^\circ$C) at a flow rate of 40 ml/min. Impedance spectra of the cells were measured after 30 min equilibrium at each operating temperature. Further, open cell voltages and current-voltage characteristics of the fuel cells were recorded (using EG&G Model 273 A) under identical conditions for each impedance measurement.

**Results and discussion**

**Solubility of dopants**

Compared to the X-ray diffraction (XRD) pattern of the LaGaO$_3$ perovskite phase shown in Fig. 2a, the XRD pattern of a sample with the intended composition La$_{0.9}$Sr$_{0.1}$Ga$_{0.8}$Mg$_{0.2}$O$_3$, shown in Fig. 2b, indicates that 10 mol% of La and 20 mol% of Ga ions may be substituted by Sr and Mg ions, respectively, without disturbing the perovskite structure. However, when 20 mol% of transition metal ions were introduced to substitute the Ga ions, shoulders at 58° and peak splitting at 68° were observed, as shown in Figs. 2c and 2d, indicating some distortion of the LaGaO$_3$ perovskite structure. Although it is still not clear, the probable cause of this lattice distortion includes (1) the difference in ionic radii between transition metal ions and Ga$^{3+}$, and (2) possible substitution of both Ga$^{3+}$ and La$^{3+}$ sites in the structure. Nevertheless, the essential features of the XRD patterns for transition metal oxide doped LaGaO$_3$ remain the same as those for LaGaO$_3$, indicating that single-phase perovskites with the formula La$_{0.9}$Sr$_{0.1}$Ga$_{0.8}$M$_{0.2}$O$_3$ (M = Co, Mn, Cr, Fe or V) were obtained and 20 mol% of these transition metal oxides are soluble in LaGaO$_3$.

**Microstructure of sintered samples**

Statistical analysis of the scanning electron microscopy (SEM) micrograph shown in Fig. 3a indicates that the porosity of the sintered La$_{0.9}$Sr$_{0.1}$Ga$_{0.8}$Mg$_{0.2}$O$_3$ sample is about 7.8%. Water-displacement measurements showed that the sintered La$_{0.9}$Sr$_{0.1}$Ga$_{0.8}$Mg$_{0.2}$O$_3$ sample has a density of about 92% of the theoretical one with negligible open porosity. Further, the open cell voltages of single fuel cells using La$_{0.9}$Sr$_{0.1}$Ga$_{0.8}$Mg$_{0.2}$O$_3$ as electrolytes were close to the theoretical values at 600–800°C, implying that open porosity in the La$_{0.9}$Sr$_{0.1}$Ga$_{0.8}$Mg$_{0.2}$O$_3$ pellet is not significant. Thus, the pores observed on the SEM micrograph are mostly closed pores. The sintering densities of transition metal oxide doped samples, La$_{0.9}$Sr$_{0.1}$Ga$_{0.8}$M$_{0.2}$O$_3$ (M = Co, Mn, Cr, Fe or V), are greatly increased. Water-displacement measurements showed that these samples are more than 98% of the theoretical densities, indicating that transition metal ions act as a sintering aid to improve the sinterability of the materials. A typical SEM micrograph of a Mn-doped sample is shown in Fig. 3b.

**Bulk conductivity in air**

The impedance spectra of samples in the system La$_{0.9}$Sr$_{0.1}$Ga$_{0.8}$M$_{0.2}$O$_3$ (M = Mg, Co, Mn, Cr, or Fe) measured in air are more or less similar. They usually contain one or two semi-circles at the intermediate frequency range. Typical impedance spectra of a Co-doped sample (La$_{0.9}$Sr$_{0.1}$Ga$_{0.8}$Co$_{0.2}$O$_3$) measured at different
temperatures in air are shown in Fig. 4a. The bulk resistance of the sample can be obtained from the intercept of the spectra with the real-axis at high frequencies. The temperature dependence of the bulk conductivities of different samples in the $La_{0.9}Sr_{0.1}Ga_{0.8}Mn_{0.2}O_3$ system in air is shown in Fig. 5a. It can be seen that introducing transitional metal ions in the Ga site in the $La_{0.9}Sr_{0.1}Ga_{0.8}Mn_{0.2}O_3$ system increased the bulk conductivity compared to LSGM, especially at low temperatures. It is also noted that the activation energies for the samples with transitional metal ions in the Ga site are much smaller than that for LSGM. Among the transitional metals studied, Co and Mn doped samples exhibit much higher bulk conductivities in air than other samples. Accordingly, these two materials may be used as the cathode materials for LSGM-based SOFCs.

Fig. 3a,b SEM micrographs of polished and thermally etched surfaces of two sintered samples: a $La_{0.9}Sr_{0.1}Ga_{0.8}Mg_{0.2}O_3$ and b $La_{0.9}Sr_{0.1}Ga_{0.8}Mn_{0.2}O_3$.

Fig. 4a–c Typical impedance spectra of a Pt|$La_{0.9}Sr_{0.1}Ga_{0.8}Mn_{0.2}O_3$|Pt cell measured at different temperatures: a $M = \text{Co}$, in air; b $M = \text{Mn}$, in $H_2$; and c $M = \text{V}$, in $H_2$.

Fig. 5a,b Temperature dependence of the bulk conductivity of $La_{0.9}Sr_{0.1}Ga_{0.8}Mn_{0.2}O_3$: a $M = \text{Mg, Co, Mn, Cr or Fe, in air}$, and b $M = \text{Mg, Mn, V, Cr or Fe, in H}_2$. The value adjacent to each symbol is the activation energy in eV for electrical conduction in the material.
Bulk conductivity in H₂

Impedance spectra of transition metal oxide doped samples measured in H₂ are similar to those in air except for that of a Mn-doped sample (La₀.₉Sr₀.₁Ga₀.₈Mn₀.₂O₃). Typical impedance spectra of La₀.₉Sr₀.₁Ga₀.₈Mn₀.₂O₃ and La₀.₉Sr₀.₁Ga₀.₈V₀.₂O₃ measured in H₂ are shown in Figs. 4b and 4c, respectively. The spectra shown in Fig. 4b indicate that significant electronic conductivity exists in the Mn-doped sample. The bulk resistance of each sample in H₂ was determined from the intercept of the impedance spectra with the real-axis at high frequencies. The temperature dependence of the bulk conductivities of different samples in the La₀.₉Sr₀.₁Ga₀.₈M₀.₂O₃ system in H₂ is shown in Fig. 5b. It was observed that La₀.₉Sr₀.₁Ga₀.₈Mn₀.₂O₃ exhibits the highest bulk conductivity among the samples studied. Further, it is noted that La₀.₉Sr₀.₁Ga₀.₈Co₀.₂O₃ disintegrated under the testing conditions, indicating that La₀.₉Sr₀.₁Ga₀.₈Co₀.₂O₃ is not stable under a reducing atmosphere and thus cannot be used as anode material. The bulk conductivity of La₀.₉Sr₀.₁Ga₀.₈Mn₀.₂O₃ is 0.08 and 0.10 S/cm at 700 and 800 °C, respectively, and this material is chemically stable in an H₂ atmosphere. Therefore, it may be used as anode material for LSGM-based SOFCs.

Ionic and electronic conductivity

The ionic transference numbers, \( t_i \), of La₀.₉Sr₀.₁Ga₀.₈M₀.₂O₃ (M = Mg, Co, or Mn) were determined from [11]

\[
\frac{t_i}{1 - t_i} = 1 - \frac{R_b}{R_t} \left( 1 - \frac{V_{oc}}{E_N} \right)
\]

where \( R_b \) and \( R_t \) are the bulk and total resistance, respectively, of the cell as determined from impedance spectroscopy, and \( V_{oc} \) and \( E_N \) are the open-cell voltage and Nernst potential across the cell, respectively.

Further, the ionic transference numbers, \( t_i \), were also calculated from the combination of oxygen permeation and impedance measurements using the following equation (M. Liu, unpublished):

\[
t_i = \left( 1 - \frac{R_b}{R_t} \right) + \frac{R_b}{E_N} \left( \frac{V_{oc}}{I_{O^2}} \right)
\]

The ionic current due to the permeation of oxygen through the oxygen concentration cell, \( I_{O^2} \), can be calculated as [12]:

\[
I_{O^2} = \frac{85.89(V_2X_2 - V_1X_1)}{T}
\]

where \( V_2 \) and \( V_1 \) are the flow rate (ml/min) of the outgoing and incoming gas, respectively, and \( X_2 \) and \( X_1 \) are the oxygen partial pressures (atm) of the outgoing and incoming gas, respectively.

Typical impedance spectra of cells using La₀.₉Sr₀.₁Ga₀.₈Co₀.₂O₃ and La₀.₉Sr₀.₁Ga₀.₈Mn₀.₂O₃ as the electrolyte measured at different temperatures are shown in Fig. 6. \( R_b \) and \( R_t \) are determined from the intercepts of the impedance spectra with the real-axis at high and low frequencies, respectively. The transference numbers of the three materials determined using Eqs. 1 and 2 are shown in Fig. 7. Figure 7a shows that La₀.₉Sr₀.₁...
Ga0.8Mg0.2O3 exhibits predominantly ionic conduction at T > 700 °C, with the ionic transference number approaching 1 at 800 °C. As discussed elsewhere (M. Liu, unpublished) the uncertainty in both open cell voltage and gas permeation measurements increases with decreasing temperature, leading to larger discrepancies in the ionic transference number at low temperatures. For the cell using La0.9Sr0.1Ga0.8Co0.2O3 as the electrolyte, the ionic transference number is less than 0.1, as shown in Fig. 7b, indicating that La0.9Sr0.1Ga0.8Co0.2O3 exhibits predominantly electronic conduction. Since the open cell voltage in an oxygen concentration cell using La0.9Sr0.1Ga0.8Co0.2O3 as the electrolyte is rather low (about 1 mV), the combination of gas permeation and impedance spectra is more reliable in determining the ionic transference number than the combination of open cell voltage and impedance spectra.

The electronic (Re) and ionic (Ri) resistance of the electrolyte and the interfacial resistance Rp of the cell can be obtained from the following equations (M. Liu, unpublished):

\[
R_e = \frac{E_N}{2I_{O^2}} - \sqrt{\left(\frac{E_N}{2I_{O^2}}\right)^2 - R_i \left(\frac{E_N}{2I_{O^2}}\right)}
\]

\[
R_i = \frac{R_p R_e}{R_e - R_b}
\]

\[
R_p = \frac{E_N}{I_{O^2}} - R_e - R_i
\]

Table 1 summarizes Re, Ri, and Rp for a cell using La0.9Sr0.1Ga0.8Mn0.2O3 as the electrolyte. It is noted that Rp is much greater than both Re and Ri. Therefore, the performance of the cell is dominated by the interfacial resistance. Accordingly, the observed open cell voltage was almost zero although the ionic transference number is as high as 0.8 at 780 °C, indicating that La0.9Sr0.1Ga0.8Mn0.2O3 is an MIEC with predominantly ionic conduction.

Similarly, Table 2 lists Re, Ri, and Rp for the oxygen concentration cell using La0.9Sr0.1Ga0.8Co0.2O3 as the electrolyte. It can be seen that Re and Rp are much smaller than Ri, indicating that the interfacial resistance is not significant and electronic conduction predominates in this material.

Table 1 The electronic (Re) and ionic (Ri) resistance of the electrolyte and the interfacial (Rp) resistance of the cell using La0.9Sr0.1Ga0.8Mn0.2O3 as the electrolyte

<table>
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<tr>
<th>Temperature (°C)</th>
<th>Re (Ω)</th>
<th>Ri (Ω)</th>
<th>Rp (Ω-cm²)</th>
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</thead>
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<td>3.70</td>
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</tr>
<tr>
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<td>780</td>
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<td>2.47</td>
<td>909.9</td>
</tr>
</tbody>
</table>

Table 2 The electronic (Re) and ionic (Ri) resistance of the electrolyte and the interfacial (Rp) resistance of the cell using La0.9Sr0.1Ga0.8Co0.2O3 as the electrolyte

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Re (Ω)</th>
<th>Ri (Ω)</th>
<th>Rp (Ω-cm²)</th>
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Fuel cell performance

Shown in Fig. 8 are the current-voltage and current-power characteristics of the three single LSGM fuel cells using different electrode materials. It can be seen that the cell using MIEC electrodes exhibited much better performance than the one using Pt electrodes. The cell performance is also improved using MIEC electrodes compared to that of the cell using traditional electrodes (LSC as cathode and CeO2-Ni as anode). At 800 °C, the...
maximum powder density of the cell with Pt electrodes was only 20 mW/cm² (corresponding to a current density of 34 mA/cm² at 0.6 V), and the maximum power density of the cell using LSC as the cathode and CeO₂-Ni as the anode was 61 mW/cm² (corresponding to a current density of 102 mA/cm² at 0.6 V), while the maximum power density of the cell with La₀.₉Sr₀.₁Ga₀.₈Co₀.₂O₃ as the cathode and La₀.₉Sr₀.₁Ga₀.₈Mn₀.₂O₃ as the anode reached 88 mW/cm² (corresponding to a current density of 148 mA/cm² at 0.6 V). Accordingly, doped LaGaO₃ MIECs seems to be better electrode materials than Pt, LSC, or Ni composite for LSGM-based SOFCs.

Impedance spectra of the three cells at different temperatures are shown in Fig. 9. The interfacial resistance of the fuel cell ($R_p$) can be calculated from the following equation [11]:

$$R_p = \frac{R_t - R_b}{1 - \frac{\epsilon_o}{\epsilon_n}}$$

Figure 10 shows $R_b$, $R_t$, and $R_p$ for the three cells at different operating temperatures. It can be seen that the $R_p$ values of the cell with MIEC electrodes are smaller than the $R_b$ values for the cell with Pt electrodes and for the cell with LSC as the cathode and CeO₂-Ni as the anode at all temperatures studied, indicating that using the MIECs as the electrode materials can reduce the interfacial resistance. It is also noted that, at $T \geq 750 ^\circ C$, $R_p$ is smaller than $R_b$ in the cell using MIEC as electrodes, implying that resistance of the electrolyte-electrode interfaces is not significant and the main power loss is due to the ohmic resistance of the electrolyte (with thickness of 1.65 mm).

Using LSC as the cathode and CeO₂-Ni as the anode for a fuel cell with LSGM as the electrolyte (thickness 0.5 mm) operated at 800 °C, Huang et al. [8] obtained a maximum power density of 270 mW/cm², whereas Ishihara et al. [13] reported a maximum power density of 710 mW/cm². From Figs. 8 and 10 it is noted that the LSGM-based cell using MIECs as electrodes has lower interfacial resistance and higher power densities than the cell using LSC as the cathode and CeO₂-Ni as the anode.

The electronic conduction in transition metal oxide doped LaGaO₃ originates from the multi-valence properties of the transitional metal ions. Accordingly, electronic conduction in these materials is a function of the dopant concentration of the transition metal ions, and it typically increases with dopant concentration within the solubility of the transition metal oxides in LaGaO₃. However, the solubility of transition metal oxides in LaGaO₃ and the optimum dopant concentration for electrode applications are yet to be determined. Consequently, it is expected that the performance of the LSGM-based fuel cells using MIECs as electrodes may be further improved by optimizing the dopant concentration and the microstructures of the MIEC electrodes through processing and by reducing the electrolyte thickness.

**Conclusion**

Transition metal oxide doped lanthanum gallates, La₀.₉Sr₀.₁Ga₀.₈M₀.₂O₃ (where M = Co, Mn, Cr, Fe or V), display not only higher conductivity but also better
sinterability than LSGM. Among the doped LaGaO₃ studied, Co-doped LaGaO₃ exhibits the highest conductivity in air and Mn-doped LaGaO₃ exhibits the highest conductivity in H₂, implying that the former may be used as a cathode whereas the latter may be used as a anode for LSGM-based SOFCs. Electrochemical measurements using an oxygen concentration cell indicate that La₀.₉Sr₀.₁Ga₀.₈Mn₀.₂O₃ is an MIEC with significant ionic conduction whereas La₀.₉Sr₀.₁Ga₀.₈Co₀.₂O₃ is an MIEC with overwhelming electronic conduction. At 800 °C, a single LSGM-based fuel cell using La₀.₉Sr₀.₁Ga₀.₈Co₀.₂O₃ as the cathode and La₀.₉Sr₀.₁Ga₀.₈Mn₀.₂O₃ as the anode shows a maximum power density of 88 mW/cm², which is better than those cells using Pt as both electrodes, or using LSC as the cathode and CeO₂-Ni as the anode under identical conditions. The performance of LSGM-based fuel cells with MIEC electrodes may be further improved by reducing the electrolyte thickness and optimizing the electrode processing.

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