Gallium-doped lanthanum germanates as electrolyte material of solid oxide fuel cells

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In this study, the effects of various amounts of Ga3⁺ dopants on the densification, phase structure, microstructure and electrical conductivity of La9.5Ge6.0O26.25 ceramics are examined. The incorporation of Ga3⁺ ions into the La9.5Ge6.0O26.25 lattices leads to the retardation of the densification and an increase in the triclinic structure, caused by the evaporation of GeO₂ and the largeness of the size difference between the Ga3⁺ ions and Ge⁴⁺ ions. Of the compositions studied, the La9.5Ge5.5Ga0.5O26.1 ceramic sintered at 1450°C shows an electrical conductivity of 4.02 × 10⁻² Scm⁻¹ at 800°C, which is higher than that of an SYSZ ceramic. The calculated thermal expansion coefficient (CTE) of this ceramic of 10.4 × 10⁻⁶ K⁻¹ appears to be compatible with those of the common adjacent materials used in solid oxide fuel cells (SOFCs). A single cell with a La9.5Ge5.5Ga0.5O26.1 electrolyte 0.51 mm in thickness is built and evaluated. The cell has Rₜ and Rₚ values of 0.80 and 0.28 Ω cm², respectively, at 850°C. The open circuit voltage (OCV) and maximum power density (MPD) of the single cell are recorded as 1.002 V and 0.24 W cm⁻².

1. Introduction

Apatite-type materials, A₁₀₋ₓMₓO₂₆₋ₙ (A = rare earth or alkaline earth; M = Si and Ge), are considered as potential candidates for the electrolytes in solid oxide fuel cells (SOFCs) in addition to common oxide ion conductors, including fluorite-structured Zr₁₋ₓYₓO₂₋₉ (YSZ) and Sm₁₋ₓCeₓO₂₋₄ (SDC) and perovskite-structured La₀.₉Sr₀.₁Ga₀.₈Mg₀.₂O₃ (LSGM). Different from the major ion conduction mechanism in fluorite- or perovskite-type materials closely relating to oxygen vacancy, it is thought that the conduction of the apatite materials occurs via interstitial oxide ions. The hexagonal structure is composed of isolated MO₄ tetrahedra-forming channels running parallel to the c-axis, with A cations located in two cavity sites, one 7 coordinate and one 9 coordinate, where the loosely bounded oxide-conducting anions are located. The oxide ions in the channels are considered mobile, leading to a high level of oxide ion conductivity.

The substitution of Si ions by Ge ions has been found to decrease sintering temperatures and improve electrical conductivities. As reported in the literature, the electrical conductivities of La₉.₃₃Ge₆O₂₇, La₉.₁₅Ge₆O₂₆ and La₉.₂₇Si₆Ge₄O₂₆ ceramics at 800°C are respectively 0.08, 0.06 and 0.01 Scm⁻¹, so all superior to that of La₉.₃₃SiO₂₆ (2.02 × 10⁻² Scm⁻¹). Lanthanum germa-nate apatites, however, evidence their downsides in poor control of microstructure and GeO₂ volatilization at high temperatures. Massive GeO₂ loss leads to the formation of another conducting phase, La₃GeO₇. It has been reported in the literature that another triclinic apatite phase exists in the La–Ge–O phase diagram. León-Reina et al. reported that for La₉.₃₃Si₆O₂₆ and La₉.₃₃Si₆Ge₄O₂₆ ceramics at 800°C are respectively 0.19 < x ≤ 0.27 were marked with hexagonal symmetry, while those with a higher La content of 0.33 ≤ x ≤ 0.42 exhibited a triclinic cell. The electrical conductivities of apatites with various La contents have been studied and reported in the literature.

Nakayama et al. showed that La₉.₃₃Ge₆O₂₆ had the highest conductivity among various La–Ge–O apatites, while León-Reina et al. found that La₉.₃₃(Ge₆₋ₓSi₄ₓ)O₂₆₋ₙ₋₁₂ apatites achieved the highest conductivity among various La₉.₃₃(Ge₆₋ₓSi₄ₓ)O₂₆₋ₙ₋₁₂ apatites.

Several doping studies on the La₃⁺ and Si⁴⁺ sites of Ge-based apatites have been conducted as regards lowering GeO₂ loss and/or raising conductivity. However, limited information is available which shows the feasibility of either Si-based or Ge-based apatites as electrolytes for SOFCs. In this study, various amounts of Ga³⁺ were substituted into the Ge sites of La₉.₃₃Ge₆₋ₓGaₓO₂₆₋ₙ ceramics. The densification, phase structure, and electrical conductivity of La₉.₃₃Ge₆₋ₓGaₓO₂₆₋ₙ ceramics were examined. SOFC button cells incorporating a La₉.₃₃Ge₆₋ₓGaₓO₂₆₋ₙ electrolyte, a La₀.₆Sr₀.₄Co₀.₂−ₓAlₓO₃₋ₘ cathode, a La₀.₆Sr₀.₄Co₉₋ₓFeₓO₃₋ₘ anode, and a La₀.₆Sr₀.₄Ni₀.₈O₄ electrolyte are fabricated.
Fe$_3$O$_4$ (LSCF)–Sm$_{0.2}$Ce$_6$O$_{17}$–y (SDC) composite cathode and a NiO–SDC composite anode were built. The electrochemical performance of the single cell was then assessed.

2. Experimental procedure

The Ga$^{3+}$-doped lanthanum germinate ceramic powders used in this study were synthesized using the solid-state reaction approach. La$_2$O$_3$ (SHOWA, reagent grade), GeO$_2$ (Kojundo Chemicals, reagent grade), and NiO (SHOWA, reagent grade) with a purity exceeding 99.9% were used as raw materials. Prior to the formulation preparation, the La$_2$O$_3$ powders were pre-heat-treated at 1100°C for 2 h to ensure the removal of absorbed water and oxygen. Oxides based on the formulations of La$_x$Ge$_{6-x}$Ga$_x$O$_{26.5}$ (with $x = 0, 0.05, 0.1, 0.3$ and $0.5$) were mixed and milled in methyl alcohol solution, using zirconia balls and polyethylene jars, for 4 h and then dried overnight in a 90°C oven. After drying, the powders were calcined at 1100°C for 6 h at a heating rate of 5°C/min$^{-1}$, re-milled in methyl alcohol for 4 h and dried overnight in a 90°C oven. For phase identification, X-ray diffraction (XRD, Siemens D5000) analysis was performed on the calcined powders. The calcined powders were subsequently mixed with a 5 wt% binder of 15 wt% PVA solution and pressed into disc-shaped compacts 9 mm in diameter and a thickness of 2 mm under a uniaxial pressure of 150 MPA. The compacts were then heat-treated at 550°C for 4 h to eliminate PVA, and sintered at temperatures ranging from 1350 to 1550°C for 4 h at a heating rate of 5°C/min$^{-1}$. The liquid displacement method was used to measure the densities of the specimens. Scanning electron microscopy (SEM, Hitachi S4700) studies on the polished and thermal-etched surfaces of the discs were conducted. The chemical bonding states in the ceramics were determined by X-ray photoelectron spectroscopy (XPS). Prior to the XPS analysis, the samples were sputter-etched with Ar$^+$ ions for 5 min to remove the top surface contaminants. The coefficients of thermal expansion of the dense ceramics were determined using dilatometrical analysis (NETZSCH 402C) at a heating rate of 5°C/min$^{-1}$. Conductivity versus temperature was evaluated by a standard four-probe method (Keithley 2400) in air at temperatures ranging from 25 to 800°C.

Commercially available materials, including Sm$_{0.2}$Ce$_6$O$_{17}$–y (SDC; Fuel Cell Materials, USA; $d_{50} = 0.53$ μm and BET surface area = 6.2 m$^2$·g$^{-1}$), La$_{9.5}$Ge$_{5.9}$Ga$_{0.1}$O$_{26.2}$, La$_{9.5}$Ge$_{5.7}$Ga$_{0.3}$O$_{26.1}$ and La$_{9.5}$Ge$_{5.5}$Ga$_{0.5}$O$_{26.0}$ powders) after calcination. All the XRD patterns of the calcined powders were indexed on a hexagonal structure (space group: P6$_3$/m, as compared to the diffraction peaks of the La$_{9.5}$SiO$_{27}$ ceramics (JCPDS #5-0291) in which the main peaks (211) and (112) at 2θ of ~30° were clearly differentiated. A small peak located at around 28° corresponding to the second phase was also visible in the calcined La$_{9.5}$Ge$_{5.5}$Ga$_{0.5}$O$_{26.0}$ powder.

Figure 2 shows the apparent density of the La$_{9.5}$Ge$_{5.5}$Ga$_{0.5}$O$_{26.0}$ ceramics with $x = 0, 0.05, 0.1, 0.3$ and $0.5$ versus the sintering temperature. The weight loss of all the doped lanthanum germinate samples associated with the evaporation of GeO$_2$ during sintering was less than 0.9%, which was not significantly different from those of common technical ceramics. The densification of the Ga$^{3+}$-doped lanthanum germinate ceramics was found to strongly correlate with the content of the dopant. For the La$_{9.5}$Ge$_{5.5}$Ga$_{0.5}$O$_{26.25}$ ceramic, a maximum sintered density of 5.83 g·cm$^{-3}$ was achieved at a sintering temperature of 1375°C. With a small quantity of Ga$^{3+}$ substitution ($x = 0.05$), the densification curve of the La$_{9.5}$Ge$_{5.5}$Ga$_{0.5}$O$_{26.25}$ ceramic followed a similar path to that observed for the La$_{9.5}$Ge$_{5.5}$Ga$_{0.5}$O$_{26.2}$ ceramic. However, as Fig. 2 shows, with a further increase in the Ga$^{3+}$ dopant to $x = 0.1$, the La$_{9.5}$Ge$_{5.5}$Ga$_{0.5}$O$_{26.2}$ ceramic revealed a much lower sintered density of 5.46 g·cm$^{-3}$ at a sintering temperature of 1350°C, as compared with the previous samples. This demonstrated that the incorporation of Ga$^{3+}$ ions into the apatite La$_{9.5}$Ge$_{5.5}$Ga$_{0.5}$O$_{26.25}$ lattices led to the retardation of the densification.

The delay in the densification was apparent for the La$_{9.5}$Ga$_{5-x}$Ge$_{5}$O$_{26.1}$ and La$_{9.5}$Ga$_{5-x}$Ge$_{5}$O$_{26.0}$ ceramic samples, whose electrochemical measurement were performed to examine the microstructure.

3. Results and discussion

In this study, Ga$^{3+}$ ions were doped into La$_{9.5}$Ge$_{6}$O$_{26.25}$ lattices to modify the electrical conductivity. Figure 1 shows the XRD patterns of the La$_{9.5}$Ge$_{6-x}$Ga$_{x}$O$_{26.25}$ ceramics with $x = 0, 0.05, 0.1, 0.3$ and $0.5$ (i.e., La$_{9.5}$Ge$_{6}$O$_{26.25}$, La$_{9.5}$Ga$_{0.5}$O$_{26.25}$, La$_{9.5}$Ge$_{5.5}$Ga$_{0.05}$O$_{26.25}$, La$_{9.5}$Ge$_{5.9}$Ga$_{0.1}$O$_{26.2}$, La$_{9.5}$Ge$_{5.7}$Ga$_{0.3}$O$_{26.1}$, and La$_{9.5}$Ge$_{5.5}$Ga$_{0.5}$O$_{26.0}$ powders) after calcination. All the XRD patterns of the calcined powders were indexed on a hexagonal structure (space group: P6$_3$/m, as compared to the diffraction peaks of the La$_{9.5}$SiO$_{27}$ ceramics (JCPDS #5-0291) in which the main peaks (211) and (112) at 2θ of ~30° were clearly differentiated. A small peak located at around 28° corresponding to the second phase was also visible in the calcined La$_{9.5}$Ga$_{5-x}$Ge$_{5}$O$_{26.0}$ powder.
sintered density continued to increase with sintering temperatures up to 1450°C. A further increase in the sintering temperature to reach maximum densification was not attempted, since the sample would experience a significant weight loss as the temperature approached 1500°C.

Figure 3 shows the XRD patterns of La$_{9.5}$Ge$_{6-y}$Ga$_y$O$_{26.05}$ ceramics at their maximum densifications. The extra peak at around 28° resulting from the second phase was absent, evidence that the initial oxide precursor was fully reacted and pure apatite compounds formed without any residual species present after sintering. The broadened XRD peaks around 26° corresponding to the overlap of the (211) and (112) peaks, particularly for the samples with a higher Ga$^{3+}$ content ($x =$ 0.3 and 0.5), clearly indicated the marked disappearance of the hexagonal apatite structure, as was refined on a triclinic cell by Leon-Reina et al.\textsuperscript{23) The disappearance of the hexagonal phase was caused by the evaporation of GeO$_2$ and the change in the La/(Ge+Ga) ratio. A further increase in the content of the Ga$^{3+}$ ions was not explored in this study due to the formation of the second phase, which revealed the limited solubility of Ga$^{3+}$ ions in the La$_{9.5}$Ge$_{6-y}$Ga$_y$O$_{26.25}$ lattices resulting from the large size of the doped Ga$^{3+}$ (0.47 Å) ions as compared to the Ge$^{4+}$ ions (0.39 Å).\textsuperscript{29) To confirm the valence states of the dopants, X-ray photoelectron spectra (XPS) on the densified La$_{9.5}$Ge$_{5.5}$Ga$_{0.5}$O$_{26.0}$ samples were recorded in the range of Ga 2p core-level photoelectron lines, as shown in Fig. 4. The intensities of the spectra corresponding to the Gallium dopant appeared to be very weak, due to their small quantities, and the peak intensity was found to slightly increase with the Ga$^{3+}$ content. The Ga 2p spectrum of the samples showed 2p$_{3/2}$ located near the 1117–1117.8 eV, which appeared to match with the binding energy of Ga 2p$_{3/2}$ of Ga$_2$O$_3$, thereby indicating the presence of the Ga$^{3+}$ ions in our La$_{9.5}$Ge$_{6-y}$Ga$_y$O$_{26.05}$ ceramic sample.\textsuperscript{30)}

Figure 5 presents the SEM micrographs of the polished and thermal-etched surfaces of the La$_{9.5}$Ge$_{6-y}$Ga$_y$O$_{26.05}$ ceramics with $x =$ 0, 0.05, 0.1, 0.3 and 0.5 at their maximum densities. After sintering at temperatures ranging from 1375 to 1450°C, the microstructure of the La$_{9.5}$Ge$_{6-y}$Ga$_y$O$_{26.05}$ ceramic featured a grain size ranging from 2 to 8 µm. The average grain size of these samples appeared to be very similar and all in the range of 3 to 4 µm. The second phase was invisible in the SEM micrographs, which validated the observation in the XRD patterns shown in Fig. 3. A few distributed pores approximately 1 µm in size were observed at the grain boundaries in the La$_{9.5}$Ge$_{5.7}$Ga$_{0.3}$O$_{26.1}$ and La$_{9.5}$Ge$_{5.5}$Ga$_{0.5}$O$_{26.0}$ ceramics, and which appeared to increase with the content of the dopant.

Figure 6 shows the Arrhenius plots of the electrical conductivities of the La$_{9.5}$Ge$_{6-y}$Ga$_y$O$_{26.05}$ ceramics with $x =$ 0, 0.05, 0.1, 0.3 and 0.5 at their maximum densities; Table 1 lists their electrical conductivities at 800°C and activation energies for conduction calculated from the Arrhenius plots. For the samples evaluated, the electrical conductivity increased as the measurement temperature increased. The Arrhenius plots of the La$_{9.5}$Ge$_{6-y}$Ga$_y$O$_{26.05}$ ceramics displayed a nearly linear behavior, indicating the absence of phase transition at temperatures ranging from 500 to 800°C, while the curves of the La$_{9.5}$Ge$_{5.9}$Ga$_{0.1}$O$_{26.2}$ ceramics showed a change in slope at temperatures around 700–750°C, evidence that the ceramics experienced a phase change during heating. For the La$_{9.5}$Ge$_{6.0}$O$_{26.25}$ ceramic...
sintered at 1375°C, the activation energy determined from the Arrhenius plot of electrical conductivity versus temperature appeared to be 1.06 eV, and the conductivity value reached 3.07 × 10⁻² S cm⁻¹ at 800°C. After sintering at 1400°C, the conductivity value of the La₉.₅Ge₅.₉₅Ga₀.₀₅O₂₆.₂₃ and La₉.₅Ge₅.₅Ga₀.₅O₂₆ ceramics at 800°C and their calculated activation energies of the conduction were 3.08 × 10⁻² S cm⁻¹ and 1.07 eV and 3.08 × 10⁻² S cm⁻¹ and 1.10 eV, respectively, which were very similar to those of the La₉.₅Ge₆₀.₂₅ ceramic. The electrical conductivities of the above three compositions appeared to be greater than those of the 8YSZ ceramic at temperatures higher than the 650°C reported in the literature. The electrical conductivity of the La₉.₅Ge₅.₇Ga₀.₃O₂₆.₁ ceramic sintered at 1450°C, with respect to temperature, appeared to be lower than that of an 8YSZ ceramic in the temperature below 700°C. As the temperature rose above 700°C, the former displayed higher electrical conductivity values than the latter, which reached 4.02 × 10⁻² S cm⁻¹ at 800°C. The activation energy of the La₉.₅Ge₅.₇₉Ga₀.₁O₂₆.₂ ceramic was estimated to be 1.48 eV in the low-temperature region (T < 650°C) and 0.62 eV in the higher temperature region (T > 650°C), indicating a phase transformation from triclinic to hexagonal symmetry. The conductivity at low temperatures was much lower, and the result of defect trapping in the low-symmetry triclinic cell. The electrical conductivities of the La₉.₅Ge₅.₇₉Ga₀.₁O₂₆.₀ ceramic at different temperatures appeared to be very similar to those of the La₉.₅Ge₅.₇₉Ga₀.₁O₂₆.₁ ceramic, whose activation energies were estimated to be 1.57 and 0.75 eV in the low- (T < 750°C) and high-temperature (T > 750°C) regions, respectively; the electrical conductivity at 800°C was 3.99 × 10⁻² S cm⁻¹.

Based on its good electrical conductivity, the La₉.₅Ge₅.₇₉Ga₀.₁O₂₆.₁ ceramic was chosen as the electrolyte material of the SOFC for further evaluation. To assess its thermal compatibility, dilatometrical analysis was performed on the La₉.₅Ge₅.₇₉Ga₀.₁O₂₆.₁ ceramic at temperatures up to 800°C. The calculated thermal expansion coefficient (CTE) of this ceramic appeared to be 10.4 × 10⁻⁶ K⁻¹, compatible with those of the common adjacent materials used in SOFCs. Figure 7 shows the cross-section SEM micrographs of the fracture surface of the single cell with a La₉.₅Ge₅.₇₉Ga₀.₁O₂₆.₁ electrolyte after electrochemical measurements. The micrographs revealed that the NiO-SDC/La₉.₅Ge₅.₇₉Ga₀.₁O₂₆.₁/LSCF-SDC single cell preserved a good mechanical integrity. The La₉.₅Ge₅.₇₉Ga₀.₁O₂₆.₁ electrolyte substrate with a 0.51 mm thickness incorporated a NiO-SDC composite anode (thickness ≈ 39.7 μm) and a LSCF-SDC composite cathode (thickness ≈ 23.8 μm) to form an SOFC single cell. The NiO oxide was reduced to Ni after the measurement. The anode and cathode layers were observed to display good adhesion to the opposite surfaces of the electrolyte layer and no delamination was found in the multilayer ceramics. As shown in Fig. 7, the electrolyte layer was marked with a dense microstructure with some closed porosity 1–2 μm in size, while the electrodes were characterized with a porous structure in which the pore contents were determined to be 30–40 vol %.

Figure 8 presents the Nyquist plots of the electrochemical impedance spectra of the electrolyte-supported NiO-SDC/La₉.₅Ge₅.₇₉Ge₀.₃O₂₆.₁/LSCF-SDC single cell measured at different

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**Table 1. Selected conductivity data for La₉.₅Ge₅.₇₉Fe₀.₅O₂₆, La₉.₅Ge₅.₇₉Mn₀.₅O₂₆, La₉.₅Ge₅.₇₉Ni₀.₅O₂₅.₇₅, and La₉.₅Ge₅.₇₉Ti₀.₂₃O₂₆.₂₅ ceramics**

| Sample            | Sintering Condition (Temp/Duration) | Sintered Density* (g/cm³) | Conductivity at 800°C (S/cm) | Activation Energy (eV) |
|-------------------|-----------------------------------|--------------------------|------------------------------|------------------------|
| La₉.₅Ge₆₀.₂₅      | 1375°C/4h                          | 5.83                     | 3.07 × 10⁻²                  | 1.06                   |
| La₉.₅Ge₅.₇₉Ga₀.₃O₂₆.₂₃ | 1400°C/4h                          | 5.90                     | 3.08 × 10⁻²                  | 1.07                   |
| La₉.₅Ge₅.₇₉Ga₀.₁O₂₆.₁ | 1450°C/4h                          | 5.82                     | 4.02 × 10⁻²                  | 0.62/1.48              |
| La₉.₅Ge₅.₅Ga₀.₅O₂₆.₀ | 1450°C/4h                          | 5.67                     | 3.99 × 10⁻²                  | 0.75/1.57              |

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temperatures. The highest frequency intercept of the impedance spectra corresponds to the total ohmic resistance of the cell ($R_0$), the lowest frequency intercept stands for the overall resistance of the cell and the distance between the two intercepts represents the total interfacial polarization resistance ($R_P$). As shown in Fig. 8, the single cell with the La$_{9.5}$Ge$_{5.7}$Ga$_{0.3}$O$_{26.1}$ electrolyte reported $R_0$ values and $R_P$ values of $0.80 \pm 0.05$, $0.30 \pm 0.05$, $0.28 \pm 0.05$, $0.27 \pm 0.05$ and $0.28 \pm 0.05$ cm$^2$, $1.2 \pm 0.1$, $1.77 \pm 0.21$, $2.59 \pm 0.21$ and $2.81 \pm 0.21$ cm$^2$ respectively, at 850, 800, 750, 700 and 650°C, respectively. Both the ohmic and polarization resistances were observed to increase as the operating temperature dropped, and their magnitudes seemed quite reasonable considering the electrolyte thickness of 0.51 mm. It is generally agreed that the variation in $R_0$ with temperature is mainly caused by the change in the resistance of the electrolyte. The $R_0$ of the single cells increased continuously from 0.80 to 4.11 Ω cm$^2$ as the measurement temperature decreased from 850 to 650°C, a typical occurrence due to the dependence of the ionic conductivity of La$_{9.5}$Ge$_{5.7}$Ga$_{0.3}$O$_{26.1}$ on temperature.

Figure 9 shows the I–V curves and the corresponding power densities of the electrolyte-supported single cell with the pure La$_{9.5}$Ge$_{5.7}$Ga$_{0.3}$O$_{26.1}$ electrolyte measured at different temperatures. The open circuit voltages (OCV) of the single cell reported 1.002, 1.015, 1.030, 1.044 and 1.058 V, respectively, at 850, 800, 750, 700 and 650°C, respectively. The OCV values were in agreement with the theoretical values, thus verifying the gas-tight sealing during the electrochemical measurement and confirming the pure ionic conduction in apatite ceramics as suggested in...
Fig. 9. J–V curves and the corresponding power densities of the electrolyte supported single cells containing a La₉.₅Ge₅.₇Ga₀.₃O₂₆.₁ electrolyte, a composite cathode of LSCF and SDC, and a composite anode of NiO and SDC measured at different temperatures.

the literature. Moreover, the nearly linearly decrease in the J–V curves indicated that the non-ohmic behavior attributed to the activation and concentrated polarization on the electrodes was minimized. The maximum power densities (MPDs) of the NiO–SDC/La₉.₅Ge₅.₇Ga₀.₃O₂₆.₁/LSCF–SDC single cell were 0.236, 0.158, 0.096, 0.057 and 0.031 W cm⁻² at the measurement temperatures of 850, 800, 750, 700 and 650°C, respectively. The decline in MPD associated with the drop in measurement temperatures of 850, 800, 750, 700 and 650°C, respectively.

4. Conclusions

In this study, La₉.₅Ge₆.₀O₂₆.₂₅ electrolytes with various amounts of Ga³⁺ dopant were prepared and evaluated. It was found that the substitution of Ga³⁺ dopant in the La₉.₅Ge₆.₀O₂₆.₂₅ ceramic resulted in the delay of the densification and the formation of a triclinic structure, caused by the evaporation of GeO₂ and the large size difference between the Ga³⁺ ions and Ge⁴⁺ ions. La₉.₅Ge₅.₇Ga₀.₃O₂₆.₁ ceramic sintered at 1450°C showed a CTE of 10.4 × 10⁻⁶/K⁻¹ and an electrical conductivity of 4.02 × 10⁻² S cm⁻¹ at 800°C. The single cell with La₉.₅Ge₅.₇Ga₀.₃O₂₆.₁ electrolyte was superior to those of SOFC cells using La₉.₀Si₆O₂₅.₅, La₉.₅Ge₆.₀O₂₅.₅, and La₉.₀Si₆.₁₇Mg₅₀O₂₆.₄ ceramics as electrolytes, as reported in the literature, thus qualifying the La₉.₅Ge₅.₇Ga₀.₃O₂₆.₁ ceramic as a potential electrolyte material for SOFCs.

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