The Influence of Microstructure and Grain Boundary on the Electrical Properties of Scandia Stabilized Zirconia

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Nanocrystalline Sc2O3 (different doping content) stabilized ZrO2 (ScSZ) powders are prepared by the hydrothermal method. Dense ScSZ ceramic pellets are fabricated by isostatically pressing and sintering at 1350°C for 2 h. 8 mol% Sc2O3 doped Zirconia possesses the highest conductivity of all the samples measured by impedance spectroscopy. Different grain size of 8ScSZ samples which are observed by scanning electron microscopy (SEM) are prepared by sintering with different temperature and different hours. The correlation between grain size and electrical properties is analyzed by impedance spectroscopy fitting and calculating with brick-layer model and Mott-Shottky model: the total grain boundary conductivity decreases but the specific grain boundary conductivity increases with the decrease in grain size of 8ScSZ; the grain boundary space charge potential decreases and the concentration of oxygen vacancies in the space charge regions increases with decreasing grain size. [doi:10.2320/matertrans.M2012385]

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1. Introduction

The cubic fluorite rare-earth doped ZrO2 materials are well-known candidates for the electrolyte of solid oxide fuel cell (SOFC) due to their high ionic conductivity, stability in both oxidizing and reducing environment and stability against the electrode materials.1-5 Of all known rare-earth doped ZrO2, Sc2O3 stabilized ZrO2 (hereinafter describe ScSZ) close to 8 mol% Sc2O3 content, has been shown to possess the highest oxygen ion mobility at elevated temperatures (0.32 S cm−1 at 1000°C).6-7 Thus the high ionic conductivity property of ScSZ has been extensively studied. The crystal structure of ScSZ is the foundation for conductivity. Undoped ZrO2 is monoclinic at room temperature (space group P21/c8,9); with the increase of temperature (at zero pressure) the material transforms to tetragonal (space groups P42/nmc) structure at 1400 K and then to a cubic fluorite structure (space groups Fm3m) at 2650 K.10-13 The doping of rare-earth oxides like Sc2O3 could stabilize the high-temperature phase of ZrO2 to the room temperature. Especially the cubic zirconia is typically a fast ion conductor due to its high diffusion coefficient of oxygen.14 Appropriate Sc2O3 doping contents could restore the cubic structure similar to that of ZrO2. But the excessive doping might decrease the ionic conductivity due to the increased association between oxygen vacancies and dopant cations to form complex defects of low mobility.15

Grain boundary is another key factor on ionic conductivity of ScSZ. At specific grain boundaries, i.e., the interfaces between adjacent grains, the conductivity of doped ZrO2 materials is ~2 orders of magnitude lower than the conductivity of bulk.16-22 this very low grain boundary conductivity is mainly attributed to the intergranular siliceous phases16-20 and the space charge effect. According to the core-space charge layer model,21 a grain boundary is consisted of a grain boundary core (crystallographic mismatch zone) and two adjacent space charge layers. The depletion of oxygen vacancies in the grain boundary space charge layer is mainly responsible for the low grain boundary conductivity without the effect of the siliceous phases. This was also proposed by Burggraaf et al.24 in 1982. More recently, Y2O3 doped ZrO2 with high purity was studied, and a Schottky barrier model25 was proposed.

In this work, ScSZ samples with different Sc2O3 dopant contents were investigated and among all samples, the 8 mol% Sc2O3 doped ZrO2 (hereby noted 8ScSZ) was sintered at the same temperature but different hours to achieve various grain size. In order to prepare high purity and weakly agglomerated samples (either of which may affect the sintering property and electrical property), the hydrothermal preparation method was applied to prepare the ScSZ powder. By comparing the impedance spectroscopy and X-ray spectroscopy of the ScSZ samples with the different dopant Sc2O3 ratio, one can establish the correlation between the ionic conductivity and the corresponding change in the microstructure of the ScSZ. The other objective of this work is to explore the grain-size-dependent specific grain boundary conductivity of ScSZ by analyzing the thickness and space charge potential of grain boundaries.

2. Experimental

2.1 Preparation

Nanocrystalline ScSZ powders were prepared by the hydrothermal urea homogeneous precipitation method. Stoichiometric solutions of ZrClO4, (A.R.; Sinopharm Chemical Reagent Company, China), ScCl3 (99.95% Sinopharm Chemical Reagent Company, China) and urea (AR; Sinopharm Chemical Reagent Company, China) in the molar ratio of Zr4+/Sc3+ = 95/5 (5 mol% Sc2O3 doped ZrO2, 5ScSZ), 92/8 (8 mol% Sc2O3 doped ZrO2, 8ScSZ) and 90/10 (10 mol% Sc2O3 doped ZrO2, 10ScSZ) were employed to prepare the stock solution (100 mL) with a cation concentration of 0.2 mol−1 in a Teflon cup (100 mL). The cup was then transferred into a stainless steel autoclave and subjected to a hydrothermal treatment at 110°C for 6 h and

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Table 1 Dopant content of Sc₂O₃ of ScSZ, relative density and activation energies for the bulk and grain boundary conductivities.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Relative density (%)</th>
<th>$E_a^{\text{total}}$ (eV)</th>
<th>$E_a^{\text{bulk}}$ (eV)</th>
<th>$E_a^{\text{gb}}$ (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5ScSZ</td>
<td>97.8</td>
<td>1.02</td>
<td>0.96</td>
<td>1.08</td>
</tr>
<tr>
<td>8ScSZ</td>
<td>97.6</td>
<td>1.25</td>
<td>1.70</td>
<td>1.44</td>
</tr>
<tr>
<td>10ScSZ (&lt;550°C)</td>
<td>97.5</td>
<td>1.46</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10ScSZ (&gt;550°C)</td>
<td>98.1</td>
<td>0.77</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2 Sintering condition (temperature and time), relative density, average grain size and activation energies for the total and specific grain boundary conductivities of 8ScSZ.

<table>
<thead>
<tr>
<th>Sintering condition</th>
<th>Relative density (%)</th>
<th>$d_g$ (nm)</th>
<th>$E_a^{\text{gb}}$ (eV)</th>
<th>$E_a^{\text{total}}$ (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1350°C × 2 h</td>
<td>97.6</td>
<td>1000</td>
<td>1.44</td>
<td>1.34</td>
</tr>
<tr>
<td>1350°C × 4 h</td>
<td>97.7</td>
<td>2500</td>
<td>1.51</td>
<td>1.51</td>
</tr>
<tr>
<td>1350°C × 36 h</td>
<td>98.1</td>
<td>4000</td>
<td>1.44</td>
<td>1.51</td>
</tr>
</tbody>
</table>

subsequently at 200°C for another 6 h under autogenous pressure in an electric oven. As the autoclave cooled down to room temperature naturally, the precipitated powders were filtered, washed with deionized water and ethanol in a centrifuge, and dried in a vacuum oven at about 110°C. The as-prepared powders were pressed isostatically into pellets with a diameter of 10–11 mm and thickness of 0.9–1.0 mm under a pressure of 20 MPa, followed by sintering under static air at 1350°C for 2 h. 8ScSZ powders were sintered at 1350°C for 2, 4 and 36 h, respectively to achieve various grain size samples. The density (shown in Tables 1 and 2) of sintered pellets was determined by Archimedes method.

2.2 Microstructural characterization

The microstructure of nano-crystalline ScSZ powders was investigated by means of transmission electron microscopy TEM (JEM 2100, 200kV, JEOL, Japan) to verify its weakly agglomerated morphology. Phase analysis was performed by X-ray diffraction using a Phillips X′Pert Pro powder diffractometer (Cu KR, 45 kV, 40 mA). Rietveld refinement was used to analyze the phase composition by the software of highscore plus.

The grain size and the microstructure of the pellets were observed using scanning electron microscopy SEM (Carl Zeiss LEO 1550 VP field emission, 3 kV excitation voltage). The transmission electron microscopy TEM (JEM 2100, 200kV, JEOL, Japan) was also used to observe the morphology of the grain boundaries of ScSZ. The TEM samples were prepared by standard methods, involving mechanical grinding to a thickness of about 0.1 mm, dimpling to about 10 μm, and then ion-beam milling to electron transparency.

2.3 Impedance spectroscopy

The conductivity of sintered pellets was measured by AC impedance spectroscopy in air from 300 to 900°C with samples equilibrated for 30 min at each temperature. Impedance spectra were measured every 10–20°C. The measurement sequence was repeated several times until the resistance at each temperature stabilized. Data were collected in the frequency range from 0.02 to 10⁷ Hz using a Solartron 1260 and voltage of 200 mV. Platinum ink (Engelhard 6082) was brushed onto both polished surfaces. The ink was applied to one side of the samples and sintered at 900°C for 2 h, this procedure was repeated for the other side. Four-wire (2 platinum wires each side) system measurement was applied in order to minimize the inductance in the measurement configuration.

Normally, three arcs in the complex impedance spectra (Fig. 1) are observed in the high-to-low frequency sequence, corresponding to the responses of the bulk, grain boundaries and electrodes, respectively. The resulting impedance spectra were analyzed in terms of an equivalent circuit model in which (depending on the temperature regime) distinct $RQ$ subcircuits were used to represent the bulk and grain boundary regions, where $R$ is an ideal resistor with $Z_R = R$, and $Q$ is a constant phase element with $Z_Q = (Y(j\omega)^n)^{-1}$, where $j$ is imaginary unit, $\omega$ is the frequency, and $Y$ and $n$ are constants with $0 < n < 1$. The capacitance, $C$, of an $RQ$ circuit was obtained from the relation $C = Y^{1/n}R^{(1/n)-1}$. The average values of $n$ obtained for bulk and grain boundary subcircuits were both close to 1 (typically ~0.95 and ~0.9, respectively), as required for meaningfully determining the capacitance by this expression. The data analysis was performed using the software package Zview (Scribner Associates Inc., Southern Pines, NC).
3. Results and Discussion

3.1 Microstructure analysis

3.1.1 Impact of Sc$_2$O$_3$ dopant content on ScSZ crystal structure

In order to prepare high-purity ScSZ powders with well-controlled compositions and microstructure, the hydrothermal homogeneous precipitation method has been employed. This approach has additional advantages of avoiding unnecessary grain growth and aggregation each of which will severely affect the sintering density and electrical property. From the TEM image shown in Fig. 2, it was observed that the as-prepared 8ScSZ powders were an assembly of homogeneous and weakly agglomerated nano-crystals.

It is well known that undoped ZrO$_2$ is in a monoclinic phase. Undoped ZrO$_2$ is difficult to densify by sintering due to the stress relaxation induced by phase transition. By doping Sc$^{3+}$ whose ionic radius is smaller than Zr$^{4+}$, the high-temperature phase could be stabilized down to room temperature. As shown in Fig. 3, different doping ratio results in different crystal structures: 5ScSZ and 8ScSZ are cubic phase, but 10ScSZ has mixed cubic and rhombohedral phases due to the decomposition of the cubic phase.

Whether ScSZ can achieve cubic phase is sensitive to the content of Sc$_2$O$_3$ dopant. Only about 5–8 mol% Sc$_2$O$_3$ dopant content could stabilize the cubic phase to room temperature. It is shown in Fig. 3 that cubic phase will decompose partially to the rhombohedral phase when the Sc$_2$O$_3$ dopant content exceeds 8 mol%. According to eq. (1), the concentration of oxygen vacancy is a constant once the Sc$_2$O$_3$ dopant content is decided.

$$\text{Sc}_2\text{O}_3\text{ZrO}_2 \rightarrow 2\text{Sc}^{3+}_2 + 3\text{O}^{2-} + \text{V}^{\cdot\cdot}_\text{O}$$  \hspace{1cm} (1)

Where Sc$^{3+}_2$ means that a Zr$^{4+}$ site is replaced by a Sc$^{3+}$; O$^{2-}$ means that O$^{2-}$ is still on its original site; V$^{\cdot\cdot}_\text{O}$ stands for an oxygen vacancy. The concentration of oxygen vacancy increases with the increase of doping level of Sc$_2$O$_3$.

According to Einstein–Nernst equation (eq. (2)), the conductivity of ScSZ sample is the function of the concentration of carrier (in this case the oxygen vacancy). Where $\sigma_i$ is the conductivity, $c_i$ is the concentration of carrier, $z_i$ is the charge of species, $e$ is the electron charge, $K_B$ is Boltzmann’s constant. Therefore, the conductivity of ScSZ dependent on temperature (Fig. 4) is the function of the different Sc$_2$O$_3$ dopant content.

$$\sigma_i = c_i z_i^2 e^2 D_i/K_B T$$  \hspace{1cm} (2)

As shown in Fig. 4, 10ScSZ has very low conductivity, which is even smaller than that of 5ScSZ whose concentration of oxygen vacancy is smaller than that of 10ScSZ under 550°C due to the appearance of the rhombohedral...
Meanwhile as shown in Table 1, 10ScSZ has higher activation energy of 1.46 eV than that of 5ScSZ of 1.02 eV and 8ScSZ of 1.25 eV. The data of activation energy show that conductivity of 10ScSZ has the tendency to be higher than that of both 5ScSZ and 8ScSZ at high temperature. However, the conductivity of 10ScSZ becomes much higher which is similar to 8ScSZ when the temperature is beyond 550°C. The activation energy of 8ScSZ and 10ScSZ beyond 550°C becomes similar, too. (Table 1) All the activation energies could be calculated by Arrhenius equation (eq. (3)).

\[
\sigma T = A \exp\left(-\frac{E_a}{K_B T}\right)
\]

Such facts suggest that a phase transition exists between 550 and 600°C, which is verified by high-temperature X-ray diffractometry. As shown in Fig. 5, 10ScSZ is in the rhombohedral phase from room temperature up to 550°C but it transforms to a cubic phase at 600°C and stays in this phase up to 1000°C. This is in agreement with the phase diagram of the Sc₂O₃-ZrO₂ system.²⁸)

### 3.1.2 Impact of Sc₂O₃ dopant content on grain size and conductivity

The doping level of Sc₂O₃ affects both crystal structure and grain size of ScSZ. As shown in Fig. 6, with the increase of Sc₂O₃ content, the grain size of sintered ScSZ pellets also increases. The grain size of 5ScSZ and 8ScSZ is about 200 and 1000 nm, respectively. The size of the majority of 10ScSZ grains is about 1000 nm, but a small portion is at about 200 nm resulting from the rhombohedral crystal structure decomposed from the cubic phase. Macroscopically, the grain boundary density of one ScSZ sample will decrease due to the increase of the grain size. The decrease of grain boundary density contributes to the decrease of the total grain boundary resistance.²⁹) The conductivity of both bulk and total grain boundary of 5ScSZ and 8ScSZ are presented in Figs. 7(a) and 7(b), respectively. Because of the frequency limitation of conventional impedance meters, it is impossible to measure the grain interior and grain boundary conductivities at high temperatures independently. However, one can extrapolate both bulk and grain boundary conductivities at high temperature with an Arrhenius equation, specifically (eq. (3)).

As a result the conductivity of total grain boundary of 8ScSZ is greater than that of the bulk below 420°C but while it’s smaller than that of the bulk above this temperature (Fig. 7(b)) because the activation energy of bulk which is 1.70 eV is higher than that of the grain boundary which is 1.44 eV shown in Table 1. But in the case of 5ScSZ, which
has a smaller grain size than 8ScSZ (Fig. 6), the higher density of grain boundaries leads to a smaller conductivity of grain boundaries than that of bulk below 450°C, but a higher grain-boundary conductivity than that of bulk (Fig. 7(a)) above this temperature because the activation energy of total grain boundary which is 1.08 eV is higher than that of the bulk which is 0.96 eV shown in Table 1. Therefore lowering grain boundary density (preparation of columnar crystal or single crystal) of 8ScSZ material used as electrolyte at the working temperature (normally 600–1000°C) is vital to future research (This is beyond the scope of the present work).

3.2 Impact of grain size of ScSZ on specific grain boundary conductivity

3.2.1 Brick layer model and specific grain boundary conductivity

The grain size of 8ScSZ pellets increases with extended sintering time (Fig. 8). The grain size of 8ScSZ sintered for 36 h is almost 4000 nm which is 4 times of the sample sintered for 2 h. The growth of the grain size results in the decrease of the total amount of grain boundaries which contributes markedly to the higher conductivity of total grain boundary (Fig. 9(a)).

![Fig. 7](image)

**Fig. 7** Temperature dependences of bulk and grain boundary conductivities for (a) 5ScSZ and (b) 8ScSZ.

![Fig. 8](image)

**Fig. 8** SEM images of 8ScSZ sintered at 1350°C for (a) 2 h average grain size is 1000 nm, (b) 4 h average grain size is 2500 nm and (c) 36 h average grain size 4000 nm.

The total grain boundary conductivity is a convolution of conductance across a single grain boundary and the number of grain boundaries within the sample. It is relatively common practice to extract from the impedance data the specific grain boundary conductivity (a real material property independent of microstructure) by making use of the “brick layer” model. While that model is constructed for a particular microstructural configuration (cube-shaped grains aligned with the direction of current flow), similar results can be derived for any arbitrary geometry. Specifically, ignoring grain boundaries parallel to the direction of current flow, the total grain boundary resistance, $R_{gb}^{total}$, of a polycrystalline material is given by eq. (4).

$$R_{gb}^{total}$$
number of grain boundary, \(L\) in both chemistry and atomic arrangement. The quantity because the bulk and grain boundary regions are similar.

**Fig. 9 Conductivity of (a) total grain boundary and (b) specific grain boundary of 8ScSZ pellets sintered in different condition with different grain size.**

\[
R_{gb}^{total} = NR_{gb}^{gb} = N\rho_{gb}^{gb} \frac{\delta}{A} \tag{4}
\]

Where \(\rho\) is resistivity, \(\delta\) is the thickness of single grain boundary, \(A\) is area and \(N\) is the number of single grain boundary and subscripts “gb” and “sp” indicate grain boundary and specific, respectively. Similarly, the capacitance of bulk and grain boundary is given by eqs. (5) and (6), respectively,

\[
C_{bulk} = \frac{\varepsilon_0 \varepsilon_{bulk}}{L_{bulk}} \tag{5}
\]

\[
C_{gb} = \frac{\varepsilon_0 \varepsilon_{gb}}{L_{gb}} \tag{6}
\]

where \(\varepsilon_0\) is the permittivity of a vacuum, \(\varepsilon\) is the relative dielectric constant, and \(L\) is the length. For a material with moderate grain size \(L_{bulk} \sim L_{sample}\), \(A_{gb} \sim A_{bulk} \sim A_{sample}\) and \(L_{gb}\) is the product of the grain boundary thickness, \(\delta\), and the number of grain boundary, \(N\). It is reasonable for \(\varepsilon_{gb} \sim \varepsilon_{bulk}\) because the bulk and grain boundary regions are similar in both chemistry and atomic arrangement. The quantity \(L_{sample}/N\) is the distance between 2 grain boundaries which is equivalent to the grain size of the brick layer model, \(d_g\).

Equations (7) and (8) could be obtained by using these approximations.

\[
\frac{C_{bulk}}{C_{gb}} = \frac{\delta N}{L_{sample}} = \frac{\delta}{d_g} \tag{7}
\]

\[
\frac{1}{\sigma_{gb}^{total}} = \frac{1}{\sigma_{gb}^{sp}} \frac{L_{sample}}{N} \tag{8}
\]

Combining eqs. (7) and (8) by using the substitution with \(\sigma = 1/\rho\) and \(\sigma = L/AR\), one obtains eq. (9).

\[
\sigma_{gb}^{sp} = \sigma_{gb}^{total} \frac{C_{bulk}}{C_{gb}} \tag{9}
\]

Specific grain boundary conductivity of ScSZ could be calculated from this analysis in which the capacitance of both bulk and grain boundary can be fitted from Fig. 10 and the total grain boundary conductivity is shown in Fig. 9(a).

As a result the conductivity of specific grain boundary of 8ScSZ is plotted in the Arrhenius form as a function of temperature. As is shown in Fig. 9(b), the conductivity of specific grain boundary of 8ScSZ decreases with the increase of grain size. The result is opposite of the case of total grain boundary of the same material. As shown in Table 2, both the activation energies of total grain boundary conductivity and specific conductivity of 8ScSZ with different grain size are similar.

**3.2.2 Space charge potential**

The “real” electrical property and specific grain boundary conductivity of 8ScSZ is affected by the purity and the space charge potential of the grain boundary. Transmission electron micrograph of 8ScSZ sintered at 1350°C for 2 h is presented in Fig. 11. This micrograph, which is representative of the overall microstructure, demonstrates that the grain boundaries are free of siliceous phase and any other amorphous phases. The grain boundaries were also studied by the energy-dispersive X-ray spectroscopy (EDXS). The different contents of Si and Sc of 8ScSZ at triple grain boundary, grain boundary and grain interior, respectively, were shown in Table 3. As a result, there is no Si or Sc segregation at grain boundaries.

According to the constancy of the electrochemical potential for mobile defects, the concentration \(C(x)\) of any dilute defect \(i\) with charge \(Z\) in the space charge layer is


Thus from eq. (10) the mobility of oxygen vacancies can be assumed to be equal for the bulk and space charge layer.23,31) Thus from eq. (10) the grain boundary resistance follows that

\[ R_{\text{gb}} \propto \frac{\sigma_{\text{bulk}}}{\sigma_{\text{gb}}} \]  

where \( \lambda_s \) is the length of space charge layer and \( \Delta \phi(x) \) is the electrostatic potential referenced to the bulk which follows that

\[ \Delta \phi(x) = \Delta \phi(0) \left( \frac{x}{\lambda_s} \right)^2 \]  

Combining eqs. (11) and (12) the grain boundary space charge potential \( \Delta \phi(0) \) is related to the specific grain boundary conductivity \( \sigma_{\text{gb}}^{\text{sp}} \) and the bulk conductivity \( \sigma_{\text{bulk}} \) by eq. (13)

\[ \frac{\sigma_{\text{bulk}}}{\sigma_{\text{gb}}} = \exp\left(\frac{2e \Delta \phi(0)/K_B T}{4e \Delta \phi(0)/K_B T}\right) \]

The depletion which was proposed as the cause of the space charge layer of 8ScSZ the positive oxygen vacancies and the concentration of \( \text{O}^{2-} \) on the surface and space charge layer of 8ScSZ the positive oxygen vacancies are depleted in this region due to the lack of negative charges.

The depletion which was proposed as the cause of the space charge region increases with decrease of the grain size of 8ScSZ. The space charge potential of the sample of 8ScSZ with the grain size of 2500 nm is slightly higher than that of the sample with the grain size of 1000 nm. But the space charge potential of the sample of 8ScSZ with the grain size of 4000 nm is much higher than those of the samples with the grain size of 1000 and 2500 nm. It suggests that the tendency of the increase of the space charge potential is not linear with the increase of grain size of 8ScSZ.

To keep the equilibrium of the concentration of oxygen vacancies and the concentration of \( \text{O}^{2-} \) on the surface and space charge layer of 8ScSZ the positive oxygen vacancies are depleted in this region due to the lack of negative charges.

\[ \frac{[V_{\text{O}}^\text{sp}] (x)}{[V_{\text{O}}^\text{sp}] (\text{bulk})} = \begin{cases} 
\exp\left(\frac{-2e \Delta \phi(0)}{K_B T} \left( \frac{x}{\lambda_s} \right)^2 \right), & (x \leq \lambda_s) \\
1, & (x > \lambda_s) 
\end{cases} \]  

Where \([V_{\text{O}}^\text{sp}] (x)\) is the oxygen vacancy concentration and \( \lambda_s \) is the thickness of the space charge layer which can be estimated as one half of the grain boundary thickness, \( \delta_{\text{gb}} \).

The oxygen vacancies concentration profile of 8ScSZ is shown in Fig. 13: the oxygen vacancies concentration in the grain boundary space charge region increases with decrease of the grain size.
The rhombohedral phase appeared in ScSZ decreases the

4. Conclusions

(1) Different dopant contents of Sc₂O₃ in ScSZ results in the formation of different crystal structure. 5 and 8 mol% Sc₂O₃ doped ZrO₂ are cubic phase. 10 mol% Sc₂O₃ doped ZrO₂ is mixed by rhombohedral phase and cubic phase. The rhombohedral phase appeared in ScSZ decreases the conductivity of ScSZ, but it can be transformed to cubic phase again when the temperature is above 550°C. (2) The increase of the dopant content of Sc₂O₃ leads to the decrease in grain size of ScSZ. But excessive dopant content brings about the re-emergence of the large grain size specifically in 10ScSZ which is attributable to the rhombohedral phase decomposed from cubic phase. (3) The grain boundaries of high-purity 8ScSZ are free of any amorphous phase and without any segregation; the total grain boundary conductivity decreases but the specific grain boundary conductivity increases with the decrease in grain size of 8ScSZ. As a result, the grain boundary space charge potential decreases and the concentration of oxygen vacancies in the space charge regions increase with decreasing grain size.

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REFERENCES