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Silver Modified Cathodes for Solid Oxide Fuel Cells
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Solid oxide fuel cells (SOFCs) have attracted much attention as a potential alternative to conventional combustion-power plants for electrical power generation due to their high efficiency together with low emission and excellent fuel flexibility. Decreasing the operating temperature to the intermediate range (500–800 °C) is an important step toward the widespread commercialization of SOFCs technology, while the lack of stable cathode material with sufficiently high activity for oxygen reduction reaction (ORR) has become the main obstacle. Recently, much effort has emerged toward the development of alternative cathode materials with enhanced ORR activity at intermediate temperatures to compromise between cost, performance, and durability. An important direction in SOFC research is the development of high-performance cobalt-free perovskite oxides as alternative electrode materials for operation at intermediate temperatures. Iron-based perovskites have received particular attention because of high abundance, low cost, and favorable stability of iron oxide. Unfortunately, the electrocatalytic activity of most iron-based perovskite electrode materials for ORR is still not high enough at intermediate temperatures.

The formation of composite electrodes has been used to improve the physical contact between the nanoparticles and the electrode surfaces. The modification of selected electrodes with some precious metals (Ag, Pd, and Pt) or perovskite oxide-based nanoparticles has been reported as significantly enhancing the catalytic activity of the electrodes toward ORR. Some potential drawbacks of the infiltration method may include non-uniform distribution of the as-prepared nanoparticles, reduced porosity of the electrode, and complicated processing procedures. Coarsening of nanoparticles at elevated temperatures is also a serious concern for most nanoparticle-modified electrodes. On the other hand, exsolution enables a novel approach to nanodesign of the electrodes increasing the effective surface area and enhancing the catalytic activity of the materials for various electrochemical applications.

Silver (Ag) is known to improve the oxygen exchange reaction activity. Ag-containing electrodes have shown high activity toward ORR making Ag as an efficient and promising component for SOFC cathodes. Attempts were made to either mix or impregnate SOFC cathodes (e.g. La,Sr,MnO3, LCM) with Ag. Problems can arise during impregnation due to low adhesion forces between the Ag precursor solutions and the ceramic cathode material. On the other hand, mechanical mixing of metals and ceramics always comprise the ductility of the metal, what makes the particles rolled to irregular flat bands destroying the microstructure of the cathode. Attempts were made to apply La0.65Sr0.3MnO3−δ as a SOFC cathode material synthesized by the Pechini method with small amounts of generally and homogeneously distributed Ag. The solubility of Ag in the La0.65Sr0.3MnO3−δ perovskite was lower than 1 wt%, while higher amounts of Ag segregated as solid metal. The SOFC cathode produced a moderate current density due to the low sintering temperature to avoid melting of Ag. Recent study has shown that Ag-modified LSM can be introduced as a novel precursor for nanosized silver decorated LSM electrode under cathodic polarization with improved stability and in situ electrochemical regeneration capability with the electrochemical intercalation/de-intercalation of Ag metal, however not fully understood and sufficiently supported in the article.

Experimental

Synthesis of the materials.—The ceramic cathode materials with the nominal composition La1−x−ySrxAgyMnO3−δ (LSAM), where \( x = 0.15 \) and \( y = 0–0.05 \) were prepared by a modified citrate complexation method (modified Pechini method) and is summarized in Figure 1. The appropriate amount of EDTA was dissolved in diluted NH4Cl solution followed by the addition of AgNO3. The solution with pH~12 was mixed for a while and citric acid was added until the nominal composition La1−x−ySrxAgyMnO3−δ was synthesized via modified Pechini method. Silver (Ag) was incorporated into La1−x−ySrxAgyMnO3−δ cathode material for solid oxide fuel cells as a catalyst precursor for oxygen reduction reaction. The La1−x−ySrxAgyMnO3−δ perovskite single phase formed at 800 °C, and the solubility of Ag in the crystal lattice of the perovskite was up to 5 mol%. The single-phase materials revealed thermal stability in different oxidizing atmospheres up to sintering temperature of the cathode at 1050 °C. The exsolution of the metallic Ag nanoparticles was performed at 350–600 °C in reducing atmosphere. Scanning electron and scanning transmission electron microcopy revealed a good mechanical contact of the Ag nanoparticles to the surface of the perovskite after reducing conditions. The electrochemical tests of the materials showed a good electrocatalytic effect of nanosized Ag toward oxygen reduction reaction. The electrochemical performance of the cathodes revealed the dependence on electrolyte material and exsolution time.

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and citric acid was optimized to be 1:2:3. The pH of the solution was adjusted to 7–8. La(NO₃)₃·6H₂O, Sr(NO₃)₂ and Mn(CH₃COO)₂·4H₂O (Sigma Aldrich and Merck, Germany; quality: ≥99.9% analytical pure) were dissolved separately in de-ionized water and slowly added to the main solution to avoid any precipitation. The solution was stirred at ambient temperature for 1 h with the following temperature increase to 90 °C for the solvent to evaporate until the gelation started. The gel was precalcined at 250 °C for 15 h in air. The lower the calcination temperature, the more amount of organic substances left. The precalcined gels were ground and placed into a round-necked vessel in HCl solution. The residue of AgCl₂ was filtered away, washed and weighed in order to determine the amount of Ag in the materials. An excess of potassium iodide (KI) and ca. 10–20 ml distilled degassed water were added. Then the vessel was closed and slightly heated in order to fully dissolve the sample. Iodometric titration of the rest of the solution was performed using 0.01 M thiosulfate (S₂O₃²⁻) solution. Starch was used as an indicator.

The synthesized powders were further ball milled for 24 h in isopropanol and mixed with 10% gadolinia-doped ceria (CGO10) or 8% yttria-stabilized zirconia (YSZ, Tosoh, Japan) in order to obtain the LSAM-based cathodes. The dry powder mixture was combined with Disperbyk180 dispersant in dipropylene glycol (DPG). Further, the appropriate amounts of graphite and Santicizer 261 were added as a poroformer and a plasticizer, respectively. Poly(methyl methacrylate) (PMMA) was used as an additive and polyvinylpyrrolidone (PVPK90) was used as a binder.

All the constituents were mixed with ZrO₂ balls for 72 h to form a paste, which was then screen-printed on top of an 8 mol% yttria-stabilized zirconia (8YSZ) and 10% gadolinia-doped ceria (CGO10) electrolytes of about 300 μm in thickness. A ‘functional layer’ of 15–20 μm in thickness consisting of a mixture of 60% 8YSZ and CGO10 and 40% LSAM was deposited. The sintering of the electrodes was carried out at 1050 °C for 2 h in air.

**Figure 1.** The schematic of the synthesis method for the LSAM materials. The ex situ exsolution conditions are included.

**Electrochemical measurements.**—The electrochemical cell tests were performed on 6 × 6 mm² symmetric cells with platinum coating as a current collector. The measurements were done in an alumina housing in 20% O₂/Ar. The electrical contact was made by means of a fine gold mesh and the samples were mounted in a setup with gold meshes kept in contact with the cells with alumina bar load. Before mounting the samples, Pt-paste (Engelhard) was added on top of the cells and sintered in situ at 850 °C. The electrochemical impedance spectroscopy (EIS) was performed using a Gamry Reference 600 potensiostat/galvanostat impedance analyzer. The setup used for the measurements has been described elsewhere. The EIS was recorded on the samples as follows. The frequency window spanned was 1 MHz to 0.05 Hz. Six points were measured at each decade. An amplitude of 24 mV was used throughout. The measurements were done at temperatures of 800, 700, 600 °C and 500 °C in the above order. The in situ exsolution was performed in 5% H₂/Ar before the measurements in 20% O₂/Ar. All measurements were done on four identical symmetrical cells. The fitting of the data was done using the Elchemia Analytical (DTU Energy) with the circuit R(R₁Q₁)R₂Q₂(R₃Q₃), where R is a resistance and Q is a constant phase element with the admittance

\[ Y = Y_0(j\omega/\omega_0)^n \]  

where \( Y_0 \) and \( n \) are found from the fitting, \( \omega \) is the cyclic frequency. In the fitting, the \( n \) values were at first allowed to vary freely. After fitting, all the data and the averages of the \( n \) values were found. The data were then fitted again using the averages of the \( n \) values using equations as follows

\[ C = R^{(1-\alpha)/2} Y_0^{1/n} \]  

\[ F_{\text{max}} = \frac{1}{2\pi} (RY_{\text{th}})^{-1/n} \]  

**Results**

The procedure of the optimized wet chemical synthesis route for La₁₋ₓSrₓAgₓMnO₃₋δ (LSAM) and exsolution of Ag nanoparticles is shown in Fig. 1. Fig. 2 summarizes the XRD results of heat-treatment conditions of LSAM materials in air. The phase pure orthorhombic Ag-doped LSAM perovskite is obtained after firing at 800 °C for 15 h in air. The lower the calcination temperature, the more amount of
metallic Ag is detected. The shift of peak positions of the orthorhombic LSAM phase are highlighted in Fig. 3. Upon increase of the Ag doping level in LSAM, the cell volume of the perovskite increase (Fig. 3 and Table II). The XRD results in Table II indicate that the exsolution process in reducing atmosphere induces expansion of the lattice according to the increase in cell parameters and cell volume, respectively. The lattice parameter of the cubic Ag structure was \( \sim 4.08 \text{ Å} \).

The weight percent of Ag in the composites are summarized in Table II showing close proximity of experimental values to the theoretical results.

The oxygen nonstoichiometry and the mean valence of Mn of the LSM15 (15 mol% Sr), LSAM152 (15 mol% Sr and 2 mol% Ag) and LSAM155 (15 mol% Sr and 5 mol% Ag) powders were evaluated by iodometry (Table I). LSAM shows slightly higher average valences of Mn ions and reduced oxygen vacancy concentration as compared with LSM15. The amount of Mn\(^{4+}\) increases with the increase of Ag doping level in LSAM. This supports doping of Ag into the A-site of the perovskite lattice as targeted. Table II shows the results of the structural XRD analysis and the BET surface area for the La\(_{1-x-y}\)Sr\(_{x}\)Ag\(_{y}\)MnO\(_{3-\delta}\) cathode materials calcined at 800–1100°C including Ag-free LSM materials. The BET surface area was around 3 m\(^2\)/g for all samples, which is larger than for the Ag-free powders (2 m\(^2\)/g), and the influence of Ag on the BET surface area can be seen. The difference in the BET surface area for the samples before and after exsolution can be determined.

Fig. 4 shows the XRD results for the exsolution of Ag nanoparticles from LSAM155 perovskite material. It can be seen that the main peaks of cubic Ag are visible after heat-treatment of LSAM materials at 450°C for 5 h in 5% H\(_2\)/Ar. The exsolution conditions were investigated experimentally at 350–600°C. The exsolution at 350°C is very slow and was chosen first to avoid decomposition of LSM phase which decomposes at >550°C into different oxides. The reduction of the LSAM material induces the shift of the XRD peak positions to lower 2\( \theta \) angles (Fig. 4).

The microstructure of LSAM155 before and after exsolution measured by SEM is shown in Fig. 5. The particle size of the materials after firing at 800°C for 15 h in air was found below 200 nm by linear intercept method (Fig. 5a). The particles are round-shaped. The microstructure of LSAM155ex material after exsolution of Ag nanoparticles is shown in Fig. 5b. Small Ag nanoparticles with different size are formed on the surface of the perovskite. Fig. 5c shows SEM micrograph in secondary electron mode (SE) with the Ag nanoparticles on the surface of the LSAM155ex perovskite. The round-shaped Ag nanoparticle size was determined below 20 nm. The same part of the microstructure of LSAM155ex material is represented in

### Table I. The results for iodometric titration of the La\(_{0.85-x}\)Sr\(_{0.15}\)Ag\(_{x}\)Mn\(^{4+}\)O\(_{3-\delta}\) materials.

<table>
<thead>
<tr>
<th>Material</th>
<th>Synthesis temperature (°C)</th>
<th>x (theor.)</th>
<th>x (exper.)</th>
<th>b</th>
<th>( \sigma )</th>
<th>Mn(^{4+}) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LSM15</td>
<td>800</td>
<td>0</td>
<td>-</td>
<td>0.013</td>
<td>3.124</td>
<td>12.4</td>
</tr>
<tr>
<td>LSAM152</td>
<td>0.02</td>
<td>0.0192</td>
<td>0.0292</td>
<td>3.131</td>
<td>13.1</td>
<td></td>
</tr>
<tr>
<td>LSAM155</td>
<td>0.05</td>
<td>0.0489</td>
<td>0.0041</td>
<td>3.168</td>
<td>16.8</td>
<td></td>
</tr>
</tbody>
</table>
Discussion

The performance of the electrodes, as reflected by the ASR values, is the best for LSAM/CGO composite cathodes with CGO electrolyte.

Figure 5. The images of the microstructure of (a) LSAM155 as-synthesized powder; (b) after heat-treatment at 450°C for 2 h in 5% H2/Ar; (c) LSAM155 with Ag nanoparticles after exsolution in SE mode and (d) BSE mode; (e) SEM image of LSAM152 after exsolution; (f) STEM image of LSAM155 and (g) STEM EDS mapping results of Ag nanoparticles.
Table III. The $R$, $C_{tot}$, and $F_{max}$ values of the individual arcs for symmetrical cells with a CGO and YSZ electrolytes in 20% O$_2$ in Ar. $R$ is given in $\Omega$ cm$^2$, $C_{tot}$ is in $\mu$F cm$^{-2}$, and $F_{max}$ is in Hz.

<table>
<thead>
<tr>
<th>T, $^\circ$C</th>
<th>Exs. time</th>
<th>$R_1$, $\Omega$ cm$^2$</th>
<th>$C_1$, $\mu$F cm$^{-2}$</th>
<th>$F_1$, Hz</th>
<th>$R_2$, $\Omega$ cm$^2$</th>
<th>$C_2$, $\mu$F cm$^{-2}$</th>
<th>$F_2$, Hz</th>
<th>$R_3$, $\Omega$ cm$^2$</th>
<th>$C_3$, $\mu$F cm$^{-2}$</th>
<th>$F_3$, Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>CGO</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>500</td>
<td>Before</td>
<td>0.60 $\pm$ 0.01</td>
<td>0.05</td>
<td>1.96</td>
<td>23.70 $\pm$ 0.07</td>
<td>0.60</td>
<td>253</td>
<td>26.46 $\pm$ 0.08</td>
<td>21.20</td>
<td>0.4</td>
</tr>
<tr>
<td>600</td>
<td></td>
<td>0.28 $\pm$ 0.06</td>
<td>0.02</td>
<td>5.38</td>
<td>2.95 $\pm$ 0.05</td>
<td>0.14</td>
<td>608</td>
<td>1.83 $\pm$ 0.11</td>
<td>2.61</td>
<td>53.2</td>
</tr>
<tr>
<td>700</td>
<td></td>
<td>0.09 $\pm$ 0.08</td>
<td>15.60</td>
<td>3060</td>
<td>0.22 $\pm$ 0.07</td>
<td>0.16</td>
<td>2280</td>
<td>0.46 $\pm$ 0.19</td>
<td>16.90</td>
<td>38.3</td>
</tr>
<tr>
<td>800</td>
<td></td>
<td>0.06 $\pm$ 0.02</td>
<td>11.20</td>
<td>245000</td>
<td>0.04 $\pm$ 0.04</td>
<td>0.24</td>
<td>22300</td>
<td>0.08 $\pm$ 0.21</td>
<td>916</td>
<td>392</td>
</tr>
<tr>
<td>YSZ</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>500</td>
<td>Before</td>
<td>5.47 $\pm$ 0.02</td>
<td>0.02</td>
<td>2160</td>
<td>51.56 $\pm$ 0.01</td>
<td>5.12</td>
<td>1.5</td>
<td>41.79 $\pm$ 0.08</td>
<td>276</td>
<td>0.3</td>
</tr>
<tr>
<td>600</td>
<td></td>
<td>1.04 $\pm$ 0.04</td>
<td>0.04</td>
<td>11700</td>
<td>6.01 $\pm$ 0.02</td>
<td>4.38</td>
<td>23.3</td>
<td>7.33 $\pm$ 0.07</td>
<td>137</td>
<td>3.8</td>
</tr>
<tr>
<td>700</td>
<td></td>
<td>0.25 $\pm$ 0.10</td>
<td>0.10</td>
<td>48200</td>
<td>1.11 $\pm$ 0.09</td>
<td>2.38</td>
<td>226</td>
<td>1.97 $\pm$ 0.03</td>
<td>68.00</td>
<td>27.1</td>
</tr>
<tr>
<td>800</td>
<td></td>
<td>0.04 $\pm$ 0.05</td>
<td>0.78</td>
<td>184000</td>
<td>0.06 $\pm$ 0.03</td>
<td>0.66</td>
<td>22200</td>
<td>0.28 $\pm$ 0.11</td>
<td>28.80</td>
<td>399</td>
</tr>
</tbody>
</table>

A screen printed symmetrical cell containing Ag-decorated LSAM reveals improved electrochemical performance of the electrode after exsolution. The exsolved Ag nanoparticles have enhanced activity of the electrodes, which is improving with exsolution time what could be attributed to the concentration of exsolved Ag nanoparticles. On the other hand, the effect in general can be explained by Fig. 10. When the electrode material is subjected to reducing atmosphere (H$_2$), the exsolution of Ag nanoparticles occurs. If the electrode material is a mixed ionic electronic conductor, almost all the exsolved Ag nanoparticles are efficient toward ORR (Fig. 10, I) and the effect on the electrochemical performance of the electrodes would be considerable. If the cathode material is only electronic conductor, not all the exsolved Ag nanoparticles would be efficient toward ORR (Fig. 10, II), and only those on triple phase boundaries (TPBs) between electrode, electrolyte and gas phases. Consequently, the effect on electrochemical performance will be gentle. All these processes are very dependent on LSAM and electrolyte composite processing, since LSAM is a good electronic conductor and composites with the electrolyte material increase ionic conductivity of the cathode and the length of TPBs. Including the fact that all the arcs in EIS (Table III) are dependent on the exsolution of Ag nanoparticles and exsolution time, it could be indicated that most of the processes occur close to the electrode–electrolyte–gas interface. The performance of the cells with YSZ is worse due to less contact points between the LSM/YSZ/Ag cathode and the YSZ electrolyte compared to the probable amount of contact points between the LSM/CGO/Ag cathodes and the CGO electrolyte. The conductivity of the electrolyte material plays an important role. As can be seen in Figs. 8 and 9 and Table III, the magnitude of all three arcs is decreased when Ag is exsolved from the single phase LSAM and is dependent on the exsolution time. The low frequency arc is the one that decreases the most and according to the literature is normally attributed to a slow redox oxygen-exchange reaction at the surface of the electrode (Eq. 4).

\[
O_{ads} + 2e^- + \nu \rightarrow O_\nu^\circ
\]

where $O_{ads}$ is adsorbed oxygen species, $e^-$ is an electron, $\nu \rightarrow O_\nu^\circ$ is an oxygen vacancy and $O_\nu^\circ$ is oxygen on the oxygen site. This arc is minimized due to a larger surface area of the cathode with small metal nanoparticles formed as a result of the exsolution in LSAM and good catalytic properties of Ag, see Fig. 5. It could be expected two scenarios enhancing the electrochemical performance of the cells. If the surface reaction represented by the low frequency arc in EIS would be diffusion controlled or due to the roughness, there would be no changes in the activation energy before and after exsolution.
but only a change in ASR.\textsuperscript{49} However, this is not the case in the current work represented by Table V as $R_3$. It can be seen that the activation energy changes before and after exsolution what implicates that it is a change in mechanism, and the performance of the electrodes is surface reaction enhanced by the catalytic activity of Ag nanoparticles. The different changes in the activation energies before and after exsolution observed for CGO and YSZ could be explained by ionic conductivity differences first. The YSZ material has a slight decrease in the activation energy after exsolution what could be due to lower ionic conductivity of YSZ in the composite and a fast surface exchange reaction. The process is not surface but diffusion limited. However, in the case of CGO an increase in activation energy can be seen which can be attributed to the thermal activation of the surface limited reaction.\textsuperscript{49}

The low frequency arc is dependent on the electrolyte material and is smaller when the CGO electrolyte is present. The partial pressures of oxygen ($p_{O_2}$) dependence of this arc is around 1/4,\textsuperscript{47} as predicted for a charge-transfer Reaction 4.\textsuperscript{50} The calculated near-equivalent capacitance of this arc is also in the range predicted for a chemical capacitance.\textsuperscript{48} The exsolution and its time affect the medium frequency arc. According to literature, this arc could be a diffusion of oxide anions through the bulk or the surface of the electrode.\textsuperscript{45,47,51} It could be speculated that if surface diffusion is the case, the medium frequency arc would depend on the presence of metal nanoparticles when the process occurs close to the electrode–electrolyte interface. The $p_{O_2}$ dependence of this arc is around 1/4.\textsuperscript{47} The high frequency arc (see Fig. 6), referring to the literature, is known to be due to transport and transfer of oxide ions or oxygen intermediates across the LSAM cathode and electrolyte interface and through the electrolyte material of the composite.\textsuperscript{45,47,48,51} The exsolution of Ag nanoparticles from the perovskite slightly affects the high frequency arc, and
Figure 9. Arrhenius plots of the total ASR as a function of temperature and in situ exsolution time in 5% H2 in Ar for the cells with (a) CGO and (b) YSZ electrolyte. The total ASR decreases with increasing exsolution time.

The near-equivalent capacity calculated using Eq. 2 is around 0.1–5 μF/cm² implying a double layer capacitance. The magnitude of this arc is much larger for the cells with YSZ electrolyte than for the cells with CGO electrolyte, indicating that the better conductivity of CGO electrolyte improves the electrode-electrolyte exchange reaction. The near-equivalent capacity is higher for the cells with CGO electrolyte, what according to the literature, indicates that there are more contact points between the composite cathode and the electrolyte. The dependence of the high frequency arc is small, approximately 1/16 indicating that the process involves oxide anions and not oxygen. It is noteworthy that the absolute ASR values of the LSM/CGO cathodes are lower compared to the LSM/YSZ cathodes (Fig. 9) implicating that the catalytic properties of the exsolved Ag from LSAM are maintained even when the screen-printed electrodes are heated to 800°C, revealing that no coarsening of the exsolved Ag nanoparticles is occurring.

From Tables IV and V it can be seen that the apparent activation energy is almost unaffected by the exsolution time what suggests that the mechanism of ORR is not much affected by the exsolution of the Ag nanoparticles, however the rate of ORR is changed.

In general, the doping of LSM with Ag can be described as follows in Reaction 5,

\[ 2La_{1-x}^+ + 3O_2^\bullet \rightarrow 2La^3+ + O_2 + 4Lax \]

This reaction is supplemented by the Reaction 6,

\[ 2La_{1-x}^+ + 3O_2^\bullet + 2Mn^{3+} \rightarrow 2La^3+ + 2Mn^{2+} + Lax \]

At low temperature oxidized Ag is stable in the perovskite lattice due to Ag2O in this lattice. The decomposition of Ag2O will depend on pO2 at different temperatures, and Ag2O would decompose at slightly higher than 200°C temperature in 0.2 atm pO2. Further, the materials are subjected to reducing atmosphere from room temperature where oxidized Ag is in the perovskite lattice. The exsolution of metallic Ag in reducing atmosphere is performed at elevated temperature due to kinetics and would be possible at room temperature in prolonged time. It is assumed that on cooling from the operation or exsolution temperature, part of Ag would be in the form of Ag2O. However, ordinary XRD measurements did not reveal Ag2O but instead metallic Ag (Figs. 2–4). The synthesis is started by complexing oxidized Ag into carbon and oxygen based materials, correspondingly increasing the stability of oxidized Ag. However, the sol-gel chemistry of Ag-based materials is quite challenging to interpret.

The XRD, thermal analysis and iodometric titration results imply that introduction of the oxygen vacancies and the concentration of Mn4⁺ induce distortion of the orthorhombic phase and slight contraction of the lattice volume at low pO2. However, Ag⁺ is considerably bigger than La3⁺ and induces overall lattice expansion. The A-site doping of LSM perovskite and exsolution of the Ag nanoparticles out from the crystal structure would induce more changes of the oxidation state for Mn together with slight reduction of the lattice. The defect equilibria of the exsolution could look as follows

\[ Ag^{2+}_{Ag} + Mn^{3+}_{Mn} \rightarrow v^{+}_{Ag} + Mn^{2+}_{Mn} + Ag^{3+}_{exs} \]  \[ Ag^{2+}_{Ag} + O^{2-}_O \rightarrow 2v^{+}_{Ag} + v^{++}_O + 1/2O_2(g) + Ag^{3+}_{exs} \]

According to the XRD results in Table II and Figs. 3 and 4, the exsolution process in reducing atmosphere induces slight expansion of the lattice what can be seen in the increase in cell parameters and cell volume. These results can be attributed only to the dominated reduction of Mn4⁺ to Mn3⁺ and Mn3⁺ to Mn⁴⁺. Referring to Fig. 4, which shows the XRD results for the exsolution of Ag nanoparticles from LSAM155 perovskite, one can conclude that the cubic Ag forms after heat-treatment of LSAM materials at 350°C for 2 h in H2/Ar. However, the exsolution process is rather slow (Figs. 8 and 9) and the detection of exsolved Ag nanoparticles is difficult by regular XRD due to very small size of the particles. One must be aware on choosing the exsolution conditions. The constant lattice parameter of the cubic Ag structure indicates that there is no strain effect between the perovskite and nanosized Ag particles. The weight percent of Ag in the composites summarized in Table II show very good agreement and close proximity of experimental values to the theoretical results. The BET surface area was around 3 m²/g for the pristine samples, which is larger than Ag-free LSM powders (Table II). The difference in the BET surface area for the samples before and after exsolution imply that the exsolution increases the total surface area of the materials and therefore the length of the TPBs so necessary for the ORR. The BET measurements were performed on the powder samples at specific conditions (see Table II). It would be expected that increasing the exsolution time as for the electrochemical cells investigated in this work, larger differences in the BET surface area would be determined.

The TGA results implicate that the phase pure LSAM perovskite is stable up to 1100°C in air (results not shown) what enables sintering of LSAM materials at high temperature in order to get good attachment...
to the electrolyte. LSAM155 loses almost 5 wt% below 1100°C in general and ~2.5 wt% at 800–1100°C what is in a good agreement with the theoretical amount of Ag by weight (Table II). This loss of 2.5 wt% could be attributed to the evaporation of Ag at high temperatures (≥ Tsp (Ag) = 961°C).

With respect to the XRD patterns (Figs. 2–4) it can be concluded that all the materials crystallized in a perovskite structure irrespective of the addition of Ag or exsolution. The successful optimized wet chemical synthesis route for LSAM and exsolution of Ag nanoparticles is shown in Fig. 1. The method is called modified Pechini method because instead of ethylene glycol we used EDTA as both complexing and polycondensation agent. Fig. 2 summarizes the heat-treatment conditions of LSAM materials in air. The phase pure orthorhombic LSAM perovskite is obtained after firing at 800°C for 15 h in air. The shifts of the peak positions and thus descent variations in the lattice parameters due to incorporation of Ag as Ag⁺ ions on the A-site position of ABO₃ perovskite lattice could be detected. The increasing doping level of Ag slightly increases the cell parameters and cell volume of the materials (see Fig. 3 and Table II). This is in a good agreement with the doping of LaMnO₃ perovskite by small amounts of Sr.⁵¹ According to Shannon, the size of six-coordinated Ag⁺ and Sr²⁺ is similar⁵⁴ and this induces the expansion of the LaMnO₃ perovskite lattice. It is noteworthy that Ag did not form any compounds as secondary phases, and only metallic Ag was detected in all the XRD patterns after exsolution of LSAM materials. The most important aspects of this procedure are the pH of each step, temperature, time of mixing and the ratio between the overall amount of cations, EDTA and citric acid. The materials in separate solutions were added dropwise in such a way that no precipitation was observed at all. The AgNO₃ is added in the very beginning due to the intended complexation with NH₃ and possible stabilization of Ag⁺ in the aqueous solution. The gelation of the mixture is slow and has to be performed on the hot plate as much as possible in order to avoid extensive degassing in the furnace. The increase in the temperature must be slow especially up to 600°C, where all the organic materials are decomposed. The method proposed in this work introduces the way to dope LSM-based materials with Ag up to 5 mol% (2.3 wt%) in contrary to the authors from Ref. 40 who stated impossibility to Ag-dope LSM more than 1 wt%. On the other hand, attempts to reproduce the procedure given in Ref. 41 was unsuccessful, since the results, methodology and support on the phase purity of the materials in the manuscript were scarce.

The SEM and STEM micrographs of the microstructure of LSAM155 before and after exsolution are shown in Fig. 5. The particle size of the materials after firing at 800°C for 15 h in air was below 200 nm (see Fig. 5a) by linear intercept method and the particles were round-shaped. The microstructure of LSAM155ex material after exsolution of Ag nanoparticles (Fig. 5b) suggests that small and stable Ag nanoparticles are formed with good adhesion on the surface of the perovskite. This is an advantage of the exsolution compared to impregnation. When compared SEM micrographs in secondary electron mode (SE) (Fig. 5e) and back-scattered electron mode (BSE) (Fig. 5d), the round-shaped Ag nanoparticles on the surface of the LSAM perovskite were determined and the size of Ag was below 20 nm. The differences in the microstructure of the LSAM155ex perovskite and Ag metal nanoparticles can be observed which are confirmed by STEM EDS analysis (Figs. 5f–5g). It is important to note that the amount of exsolved Ag nanoparticles on the surface of LSAM perovskites was proportional to the Ag doping level (see Fig. 5). Attempts were made to observe the discrete exsolved Ag nanoparticles by transmission electron microscopy (TEM). However, the Ag nanoparticles were difficult to distinguish in terms of mass thickness contrast due to similar density with the LSM. Also, high-resolution TEM images were mainly dominated by lattice fringes from the LSM.

### Conclusions

Laₓ₋₀.₅Srₓ₋₀.₅AgᵧMnO₃₋₅ (LSAM, y = 0–0.05) were synthesized by the modified Pechini method. The materials were applied in composites with CGO and YSZ as symmetric cells at 500–800°C for the electrochemical oxygen reduction reaction. The solubility of Ag in

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**Table IV. Activation energies (eV) of the two types of cells in 20% O₂ in Ar before and after exsolution in 5% H₂ in Ar.**

<table>
<thead>
<tr>
<th>Electrolyte</th>
<th>Exsolution time</th>
<th>0 h</th>
<th>3 h</th>
<th>6 h</th>
<th>12 h</th>
</tr>
</thead>
<tbody>
<tr>
<td>CGO</td>
<td></td>
<td>1.32 ± 0.03</td>
<td>1.31 ± 0.02</td>
<td>1.27 ± 0.03</td>
<td>1.32 ± 0.06</td>
</tr>
<tr>
<td>YSZ</td>
<td></td>
<td>1.32 ± 0.08</td>
<td>1.33 ± 0.08</td>
<td>1.33 ± 0.08</td>
<td>1.34 ± 0.09</td>
</tr>
</tbody>
</table>

**Table V. Activation energies (eV) of different arcs for the two types of cells in 20% O₂ in Ar before and after in situ exsolution in 5% H₂ in Ar.**

<table>
<thead>
<tr>
<th>Electrolyte</th>
<th>R</th>
<th>Exsolution time</th>
<th>0 h</th>
<th>3 h</th>
<th>6 h</th>
<th>12 h</th>
</tr>
</thead>
<tbody>
<tr>
<td>CGO</td>
<td>R₁</td>
<td>1.28 ± 0.16</td>
<td>1.28 ± 0.14</td>
<td>1.30 ± 0.14</td>
<td>1.29 ± 0.22</td>
<td></td>
</tr>
<tr>
<td></td>
<td>R₂</td>
<td>1.55 ± 0.10</td>
<td>1.53 ± 0.11</td>
<td>1.49 ± 0.11</td>
<td>1.53 ± 0.10</td>
<td></td>
</tr>
<tr>
<td></td>
<td>R₃</td>
<td>1.17 ± 0.09</td>
<td>1.32 ± 0.06</td>
<td>1.37 ± 0.08</td>
<td>1.32 ± 0.09</td>
<td></td>
</tr>
<tr>
<td>YSZ</td>
<td>R₁</td>
<td>1.17 ± 0.12</td>
<td>1.17 ± 0.11</td>
<td>1.17 ± 0.09</td>
<td>1.17 ± 0.10</td>
<td></td>
</tr>
<tr>
<td></td>
<td>R₂</td>
<td>1.55 ± 0.21</td>
<td>1.61 ± 0.23</td>
<td>1.62 ± 0.26</td>
<td>1.68 ± 0.28</td>
<td></td>
</tr>
<tr>
<td></td>
<td>R₃</td>
<td>1.28 ± 0.04</td>
<td>1.16 ± 0.13</td>
<td>1.20 ± 0.12</td>
<td>1.20 ± 0.14</td>
<td></td>
</tr>
</tbody>
</table>

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**Figure 10.** Possible mechanisms of exsolved Ag nanoparticles toward ORR.
the La$_{1-x}$Sr$_x$Ag$_x$Mn$_{1-x}$O$_3$ perovskite revealed to be up to 5 mol% with the good stability of the single phase materials in air and argon. The increased doping of the perovskite oxide induced expansion of the lattice volume. SEM images and XRD measurements showed the formation of around 20 nm very finely and homogeneously distributed Ag nanoparticles on the LSAM surface after a reductive heat-treatment at 350–600 °C in 5% H$_2$/Ar, with the Ag nanoparticle concentration influenced by the reduction temperature and Ag-doping level in LSM. The specific surface area of the materials increased after exsolution, revealing to be up to 5 mol% with nanoparticles on the LSAM surface after a reductive heat-treatment. The good stability of the single phase materials in air and argon. The improved doping of the perovskite oxide induced expansion of the solid oxide fuel cells and electrolysers’ Nature Energy, 1, 15014 (2016).

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10. Y. Zeng, A. Hirano, N. Imanishi, Y. Takeda, O. Yamamoto, and Y. Liu, “Silver Infiltrated La$_{0.6}$Sr$_{0.4}$Co$_{0.2}$Fe$_0.8$O$_3$ cathodes” J. Phys. Chem. C, 116, 3503 (2012).
12. J. Zhang, Y. Ji, H. Gao, T. He, and J. Liu, “Composite cathode La$_{0.6}$Sr$_{0.4}$Co$_0.2$Fe$_0.8$O$_3$–δ for intermediate temperature solid oxide fuel cells” J. All. Comp., 512, 322 (2005).
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17. J. Zhang, Y. Ji, H. Gao, T. He, and J. Liu, “Composite cathode La$_{0.6}$Sr$_{0.4}$Co$_0.2$Fe$_0.8$O$_3$–δ for intermediate temperature solid oxide fuel cells” J. All. Comp., 512, 322 (2005).
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