Characterization of (La1-xSr)xMnO3 and Doped Ceria Composite Electrodes in NOx-Containing Atmosphere with Impedance Spectroscopy

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The 350-S flue gas analyzer from Testo was used to measure the concentration of NO and NO2 in Ar, and 0.75% NO + 5% O2 in Ar. Furthermore, the setup was heated to 850°C to come into contact with the gold net and the electrodes, and this was done in air.

Afterward, electrochemical measurements were done at 600, 500, and 400°C in different atmospheres: air, 1% NO in Ar, 1% NO2 in Ar, and 0.75% NO + 5% O2 in Ar. Furthermore, the LSM50/CPO20 electrodes were subjected to EIS in 1% N2O in Ar at 500 and 600°C. A gas flow of 100 mL/min was used unless anything else is stated.

The symmetrical cells were placed in a setup, as shown in Fig. 1. Gold wires and a gold net were used as current collectors. Platinum cannot be used because it is catalytically active in the decomposition of nitrogen oxide.

The symmetrical cells were examined with focused ion beam–scanning electron microscopy (FIB–SEM) to view the microstructure. The sample was prepared by mounting in a Cold Mount resin supplied by Structure Probe Inc. at atmospheric pressure. A Zeiss XB 1540 CrossBeam was used for both SEM imaging and FIB milling. The accelerating voltage was 10 kV, and the SE2 detector of the XB 1540 was used. Furthermore, the polished cross section of the cells mounted in epoxy was examined in a Hitachi tabletop microscope (TM1000).

Gold paste with 20 wt % carbon was painted on the sides of the symmetrical cell as a current collector. The carbon was added as a pore former.

The symmetrical cells were placed in a setup, as shown in Fig. 1. Gold wires and a gold net were used as current collectors. Platinum cannot be used because it is catalytically active in the decomposition of nitrogen oxide.

Four small cells with similar electrodes were placed in an oven with a controlled atmosphere. The setup was heated to 850°C to remove the carbon in the gold paste and to make the gold paste come into contact with the gold net and the electrodes, and this was done in air.

Afterward, electrochemical measurements were done at 600, 500, 400, and 300°C in different atmospheres: air, 1% NO in Ar, 1% NO2 in Ar, and 0.75% NO + 5% O2 in Ar. Furthermore, the LSM50/CPO20 electrodes were subjected to EIS in 1% N2O in Ar at 500 and 600°C. A gas flow of 100 mL/min was used unless anything else is stated.

The impedance of the electrode reveals to which degree it is resisting the polarization. When the cell is polarized, current runs and the electrochemical processes can take place; i.e., the electrodes are active and surface reactions with NO2 can occur. So, the impedance can tell how hindered the electrodes’ activity is. Usually, the impedance spectrum consists of several overlapping arcs, which can be separated by fitting equivalent circuits to the experimental data.

Ideally, the polarization impedance is composed of several resistances (R) with associated capacitances (C). These RC units connected in series make up the total impedance spectrum. The constant phase elements (CPEs) are used instead of capacitances because of the nonideal behavior of the system. The impedance for the CPE can be seen in Eq. 4.

\[
Z = \frac{1}{Y_0(j\omega)^n} \tag{4}
\]

\[
RQ \text{ elements replace } RC, \text{ but the } Q \text{ values are dependent on the frequency and cannot be directly compared to the capacitance. Therefore, the equivalent capacitance (EC), also called } C_w \text{ defined in Eq. 5, is used, which is the capacitance calculated from the sumit frequency of the arc, as described in Ref. 16.}
\]

\[
C_w = R^{(1-n)/n}Q^{1/n} \tag{5}
\]

When the atmosphere is changed, the pO2 changes. The LSM, CGO, and CPO electrodes desorp O2 when the pO2 is low, thereby changing the electrodes’ properties. This should be taken into account when viewing the results for measurements in atmospheres with changing pO2.

The data obtained were analyzed with “Equivalent circuit for Windows” from University of Twente. The simplest possible fit with series-connected (RQ) elements was sought for. Then, the arcs found were compared, and some trends in α values (see Eq. 4) and ECs were recognized. Average α values were found for similar arcs, and the data were remodeled holding the α values constant. The EC and resistances obtained were assumed to represent real physical processes.

More than 180 impedance spectra were used for the analysis, varying the type of electrode, temperature, atmosphere, and flow rate.

\[
\text{Microstructure.} \quad \text{The thickness of the electrodes was approximately } 20 \mu\text{m, and the structure was porous. The microscopy pictures showed mostly small particles of less than } 1 \mu\text{m diameters along with some larger particles of up to } 5 \mu\text{m diameters. The FIB was used to mill a trench in the cell and a picture of the cut can be seen in Fig. 2, where both the LSM50/CPO20 electrode and some of the dense CGO electrolyte are visible. The electrode appears to be slightly disconnected from the electrolyte. This is likely an artifact from the preparation of the sample for microscopy, but it still indicates that the contact between the electrodes can be improved.}
\]

\[
\text{Data treatment.} \quad \text{The difference between the high frequency (HF) and low frequency (LF) intercepts with the x-axis in the impedance spectra is the polarization resistance of the electrodes of the cell, } 2R_p, \text{ as shown in Fig. 3.}
\]

For the three types of composite electrodes, three to four arcs were identified in the impedance spectra depending on temperature, electrode composition, and atmosphere.

The following steps were used to treat the large amount of EIS data.

\[
2R_p \quad \text{as shown in Fig. 3.}
\]
1. An equivalent circuit was fitted to every set of impedance spectra without any restrictions on values of parameters or number of arcs.

2. Then, the resulting equivalent circuits were compared. Arcs appearing in the multiple impedance spectra with similar capacitances and $\alpha$ values were identified.

3. For the identified arcs, average $\alpha$ values were calculated.

4. The data were fitted again, this time with the identified number of arcs with average $\alpha$ values locked.

To use this approach, it is important to have many impedance spectra, both for similar cells under identical conditions, but also varying parameters such as atmosphere, temperature, and flow rate. This is necessary because there are many free parameters in the fit, and more EIS data ensure a more realistic picture.

As an example, the impedance spectra for the LSM50/CPO10 electrodes in 1% NO in Ar at 600°C could be fitted with two to four arcs. It can be determined visually from the spectrum in Fig. 4 that at least two arcs are present: a large dominating LF arc and a smaller arc at higher frequencies. By enlarging the HF area, it is seen that for the fit with two arcs, the middle frequency (MF) arc cannot fully model the HF data points. Adding another or two other arcs provides a better fit in the HF range, and the $\chi^2$ value decreases from $2.5 \times 10^{-3}$ to $2.1 \times 10^{-4}$ and $1.6 \times 10^{-4}$. The fit with four arcs only decreases the $\chi^2$ 25% extra compared to the fit with three arcs, and it is seen in Fig. 5 that the main part of the extra HF arc is located outside the experimental data range. Applying an extra arc nearly always improves the fit but does not necessarily have any physical meaning to the system. Also, adding extra unknown parameters to be fitted from the same amount of data increases the uncertainty, so the smallest number of arcs should be used to get a reasonable fit. Therefore, the fit with three arcs is assumed to be optimal. It is close to the experimental data both at HF and LF, and the decrease in $\chi^2$ by adding another arc is very little.

The average $\alpha$ values for the LSM50/CPO electrodes were 1 for the LF arc, 0.7 for the MF arc, and 0.35 for the HF arc. The very low $\alpha$ value for the HF arc raises the question of whether it represents a real process or HF measurement errors. Fitting the spectra with the average $\alpha$ values did not change the $\chi^2$ value, which indicates that the average $\alpha$ values are correct.

The next step is to repeat the approach for the sets of impedance spectra recorded at different temperatures and for other types of electrodes and to compare the arcs identified. This may lead to sets of arcs with average $\alpha$ values, which can be used for all impedance spectra within a group. For instance, electrodes with LSM50 and CPOX ($X = 10, 20$) in 1% NO in Ar at 500–600°C can be fitted with the same set of arcs. The impedance plot for the LSM50/CPO10 cells in air at 600°C were composed of three arcs, as seen in Fig. 6. Some impedance spectra were better fitted with four arcs, such as the spectra for the LSM15/CGO10 electrodes in 1% NO in Ar at 600°C (see Fig. 7). The data points measured at LF sometimes showed time dependence; i.e., the system was not stable over the time period that the measurement requires. Therefore, some of these points were disregarded in the fitting process.

The apparent activation energy was calculated from the slope of the logarithm of the inverse resistance as a function of the inverse
temperature. In some cases, the points were very close to linearity, while in other cases, the points form a curve, and there are probably two activation energies.

The overall apparent activation energy calculated for the total $R_p$ for all the cell types can be seen in Table I. The apparent activation energy is the activation energy calculated from an approximate straight line disregarding the value of $R^2$, so in some cases, it is an average of two (or more) different activation energies. The total $R_p$ can be used as a crude estimate of the activity of the electrodes in $\text{NO}_x$, although it consists of resistances from several different electrode reaction steps, which likely have different activation energies. The standard deviation between the small cells are noted along with the square of the correlation coefficient value ($R^2$) for the linear regression.

Air.— In the impedance spectra for all types of cells in air, there was one large frequency arc and two to three smaller arcs at higher frequencies. The large arc had an EC in the range of $10^{-3}$–$10^{-2}$ F cm$^{-2}$ depending on electrodes and temperature (see Fig. 6, for example). Typically, there were three to four arcs in the impedance spectra. For the cells with LSM15/CGO10 electrodes, there were three arcs at $600^\circ\text{C}$ and four arcs at the lower temperatures. The impedance plots for cells with electrodes of LSM50/CPO10 were also composed of three to four arcs, while only three arcs were found in the impedance spectra for cells with electrodes of LSM50/CPO20 in air.

$\text{NO}_x$.— When the cells were subjected to impedance spectroscopy in an atmosphere of $1\% \text{ NO in Ar}$, three to four arcs were necessary to model the spectra. A large arc at very low frequencies dominated the spectra, followed by a smaller arc in the MF region and some smaller arcs in the HF end (see Fig. 4).

The EC of the LF arc increased with the content of Pt. The LF arc did not increase as much with decreasing temperature as the MF arc. As a result, the MF arc dominated at the lower temperatures, and at $300^\circ\text{C}$, the LF arc could not be separated from the spectra. The activation energy for the MF and LF arcs along with their EC for the three electrodes can be found in Table II. Figure 8 shows the resistance of the HF, MF, and LF arcs for LSM15/CGO10 electrodes.

The flow of gas was changed from 100 to 10 mL/min. This had a large effect on the LF arc in the NO spectra (see Fig. 9), and $R_{LF}$

### Figure 6
Impedance plot for LSM50/CPO10 electrodes in air at $600^\circ\text{C}$ along with the deconvolution of the data (dotted lines). For the solid points, the frequency of the data point is given in hertz.

### Figure 7
Impedance plot for LSM15/CGO10 electrodes in 1% NO in Ar at $600^\circ\text{C}$ along with the deconvolution of the data (dotted lines). For the solid points, the frequency of the data point is given in hertz.

### Table I
The overall apparent activation energy for electrodes in air, 1% NO in Ar, 1% NO$_2$ in Ar, and 0.75% NO + 5% O$_2$ in Ar over the temperature range of 300–600°C in a flow of 100 mL/min together with the corresponding $R^2$ values for the fit and $R_p$ values at 600°C.

<table>
<thead>
<tr>
<th></th>
<th>LSM15/CGO10</th>
<th>LSM50/CPO10</th>
<th>LSM50/CPO20</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Air</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$E_a$ (eV)</td>
<td>0.88 ± 0.01</td>
<td>1.06 ± 0.06</td>
<td>1.11 ± 0.02</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.972</td>
<td>0.978</td>
<td>0.965</td>
</tr>
<tr>
<td>$R_p$ (600°C) (Ω cm$^2$)</td>
<td>8.8 ± 0.6</td>
<td>8.3 ± 0.9</td>
<td>2.9 ± 0.5</td>
</tr>
<tr>
<td><strong>NO</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$E_a$ (eV)</td>
<td>0.55 ± 0.01</td>
<td>0.40 ± 0.03</td>
<td>0.34 ± 0.02</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.988</td>
<td>0.965</td>
<td>0.912</td>
</tr>
<tr>
<td>$R_p$ (600°C) (Ω cm$^2$)</td>
<td>31 ± 1</td>
<td>76 ± 3</td>
<td>48 ± 6</td>
</tr>
<tr>
<td><strong>NO$_2$</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$E_a$ (eV)</td>
<td>0.75 ± 0.01</td>
<td>0.88 ± 0.01</td>
<td>0.86 ± 0.01</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.996</td>
<td>0.996</td>
<td>0.993</td>
</tr>
<tr>
<td>$R_p$ (600°C) (Ω cm$^2$)</td>
<td>6.3 ± 0.3</td>
<td>5.7 ± 0.6</td>
<td>2.7 ± 0.1</td>
</tr>
<tr>
<td><strong>NO + O$_2$</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$E_a$ (eV)</td>
<td>0.97 ± 0.01</td>
<td>0.86 ± 0.01</td>
<td>0.72 ± 0.11</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.999</td>
<td>0.993</td>
<td>0.999</td>
</tr>
<tr>
<td>$R_p$ (600°C) (Ω cm$^2$)</td>
<td>7.2 ± 0.2</td>
<td>3.6 ± 0.5</td>
<td>2.4</td>
</tr>
</tbody>
</table>

### Table II
$E_a$ values together with the corresponding $R^2$ values for the fit, EC values, $R_{MF}$, and $R_{LF}$ values at 600°C for MF and LF arcs in 1% NO in Ar with a flow of 100 mL/min.

<table>
<thead>
<tr>
<th></th>
<th>LSM15/CGO10</th>
<th>LSM50/CPO10</th>
<th>LSM50/CPO20</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>MF</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$E_a$ (eV)</td>
<td>0.64 ± 0.02</td>
<td>0.67 ± 0.03</td>
<td>0.63 ± 0.05</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.990</td>
<td>0.977</td>
<td>0.977</td>
</tr>
<tr>
<td>EC (F cm$^{-2}$)</td>
<td>8 × 10$^{-3}$ to 5 × 10$^{-3}$</td>
<td>3 × 10$^{-4}$ to 5 × 10$^{-4}$</td>
<td>5 × 10$^{-4}$ to 2 × 10$^{-2}$</td>
</tr>
<tr>
<td>$R_{MF}$ (600°C) (Ω cm$^2$)</td>
<td>6.8 ± 0.5</td>
<td>5.8 ± 0.6</td>
<td>5 ± 0.1</td>
</tr>
<tr>
<td><strong>LF</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$E_a$ (eV)</td>
<td>0.34 ± 0.02</td>
<td>0.48 ± 0.01</td>
<td>0.46</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.980</td>
<td>0.978</td>
<td>0.998</td>
</tr>
<tr>
<td>EC (F cm$^{-2}$)</td>
<td>1 × 10$^{-2}$ to 1 × 10$^{-1}$</td>
<td>2–4 × 10$^{-1}$</td>
<td>3–7 × 10$^{-2}$</td>
</tr>
<tr>
<td>$R_{LF}$ (600°C) (Ω cm$^2$)</td>
<td>6.8 ± 0.5</td>
<td>68 ± 2</td>
<td>42 ± 7</td>
</tr>
</tbody>
</table>
NO2—An equilibrium between NO, O2, and NO2 may be established according to Eq. 6, and due to fast kinetics at high temperatures, a part of the NO2 present in the inlet gas stream is converted into O2 and NO.

\[
\text{NO}_2 \leftrightarrow \text{NO} + \frac{1}{2} \text{O}_2 \quad \text{[6]}
\]

The concentration of NO2 described for the experiments in this section is thus based on the concentration in the inlet gas stream, while the actual concentration around the cell might be different. The Testo 350-S flue gas analyzer was used to measure the ratio between NO and NO2 in the temperature range 400–600°C.

Increased with increasing flow rate. This phenomenon was observed for both the LSM50/CPO10 and LSM50/CPO20 cells in the temperature range 400–600°C.

Discussion

Matching of arcs to processes.—Several distinct arcs are seen in the impedance plots, and we tried to match these arcs to the termine exactly how much NO2 was present. The ratios between NO2 and NO were 2.7 and 0.9 at 400 and 500°C, respectively, while it was as low as 0.7 at 600°C.

Three to four arcs were found in the impedance plots for cells in 1% NO2 in Ar. There were two large arcs, one at MF and one at LF. The resistance of the MF arc decreased more with temperature than the LF arc, and at 400°C, the LF arc could not be seen anymore. When the impedance plots for LSM15/CGO10 electrodes in 1% NO2 in Ar at 500 and 600°C (Fig. 10 and 7) are compared, the MF arc clearly decreases much more with temperature than the LF arc.

For the electrodes containing CPO, the resistance of the LF arc did not seem to vary with temperature, as it could only be seen in the impedance spectra at 500 and 600°C, and even at 500°C, it was merely a distortion of the spectra in the LF end. The EC for this arc was in the range of 4 × 10−2 to 6 × 10−1 F cm−2 for the LSM50/CPO10 and LSM50/CPO20 electrodes. For the LSM15/CGO10 electrodes, an activation energy of 0.58 ± 0.03 eV was calculated for the LF arc with an EC in the range 1–2 × 10−2 F cm−2. But in the LSM15/CGO10 electrodes, there was another arc present at an even lower frequency at 600°C with an EC equal to 1.9 × 10−2 F cm−2. The activation energy for the MF arc for the three types of electrodes together with the corresponding EC range can be seen in Table III.

Table III. \(E_a\) values together with the corresponding \(R^2\) values for the fit, EC, and \(R_{MF}\) values at 600°C values for resistance of MF arc in 1% NO2 in Ar.

<table>
<thead>
<tr>
<th>Electrode</th>
<th>(E_a) (eV)</th>
<th>EC (F cm−2)</th>
<th>(R_{MF}(600°C)) (Ω cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LSM15/CGO</td>
<td>0.82 ± 0.04</td>
<td>(9 \times 10^{-4}) to (2 \times 10^{-4})</td>
<td>2.420 ± 0.005</td>
</tr>
<tr>
<td>LSM50/CPO10</td>
<td>1.00 ± 0.01</td>
<td>(1 \times 10^{-4}) to (1 \times 10^{-2})</td>
<td>3.3 ± 0.7</td>
</tr>
<tr>
<td>LSM50/CPO20</td>
<td>0.73 ± 0.02</td>
<td>(6 \times 10^{-4}) to (7 \times 10^{-2})</td>
<td>1.5 ± 0.2</td>
</tr>
</tbody>
</table>
processes. Some of the arcs described in the Results section are called MF and LF because of their location in the impedance plot, but the EC and summit frequency depend on the temperature. Therefore, it would be more convenient to use another naming system, and we used the same names that Jørgensen and Mogensen used in Ref. 18 where five types of arcs, A–E, were identified.

In the HF area of the impedance plots, one or two small arcs seem to be present for all the impedance plots. They are not affected by the change in atmosphere nor flow, but they do depend on temperature. Typically, the activation energy is around 1 eV, and the arcs are quite depressed with values around 0.4–0.6. We believe that these arcs are similar to the arcs of types A and B, which cannot always be separated.

These arcs are related to the transport of oxide ions across and through the LSM/doped ceria interface into the dense electrolyte. An MF arc is also identified in many of the impedance arcs. For the spectra recorded in air, the summit frequency of this arc is around 1 Hz for all the tested electrodes at 600°C, which corresponds with the range given in Ref. 18 for the C arc at 850°C. The processes of arc C are believed to be due to adsorption, surface diffusion, and transfer across the triple phase boundary (TPB). Therefore, the C arc is dependent on the length of the TPB. The activation energy for the C arc in air is around 1.4–1.6 eV for this work, which overlaps with the values reported in Ref. 18 (1.5–2.0 eV). The α value for the MF arc is typically 0.7–0.8 depending on the type of electrode and atmosphere.

When the atmosphere is 1% NO in Ar, the activation energy for the C arc decreases from 0.5 to 0.7 eV, while it is higher for the CPO-containing electrodes in 1% NO2 in Ar (1.1–1.2 eV).

All the electrodes in the NO-containing atmosphere had a very large LF arc present in the impedance spectra in the temperature range of 400–600°C. Especially for the electrodes containing CPO, the LF arc had a high EC, 2–4 $\times$ 10^−1, and 3–7 $\times$ 10^1 F cm^−2 for LSM50/CPO10 and LSM50/CPO20, while LSM15/CGO10 had an EC in the range $1 \times 10^2$ to $1 \times 10^3$ cm^−2. The α value was very high, around 0.9–0.98, and in some cases the arc could be fitted with an RC element instead of an RQ element.

Variation in the flow rate had a large effect on the size of all the LF arcs, and the resistance increased with the flow rate, as illustrated in Fig. 9.

If the 500 and 600°C impedance plots for the LSM50/CPO10 cells in 1% NO in Ar with flow rate of 10 mL/min are compared (see Fig. 13), it can be seen that the LF arc did not increase with decreasing temperature. So, for a flow of 10 mL/min, there is no activation energy, while there is some temperature dependence at a flow rate of 100 mL/min.

An LF arc with a high α value would usually be associated with conversion impedance, but this arc is not a typical conversion arc as the resistance increases with flow rate, which is the opposite of what is expected for a conversion arc. Conversion impedance was seen for a three-electrode cell, where the working and reference electrodes are in separate atmospheres.

The LF arc must somehow be related to the chemical reactions in the NO3 system as it is only seen here. A process that would fit a conversion impedance could be a reaction, which is impeded by lack of a necessary intermediate reactant. When 1% NO is present and when we increase the flow rate, more NO gets into contact with the electrode, so reactions with NO are not hindered by the shortage of reactants.

NO3 can be formed catalytically from NO by La1−xSrMnO3 (x = 0.05, 0.15, 0.25, 0.35, and 0.5) in the temperature range of 200–500°C. So, a reaction involving NO3 as one of the reactants limited by the low concentration of NO3 could be the cause of the LF arc. NO3 is often suggested as an intermediate, but it is not stable at high temperatures. Therefore, it is not likely that a reaction with NO2 as the limiting intermediate is causing the LF arc at 500 and 600°C, although it can be present as a short-lived intermediate.

Rg is more than 15 times larger for LSM50/CPO20 electrodes in 1%
N$_2$O than in 1% NO$_2$ in Ar, and also, the $R_p$ of the electrodes in 1% N$_2$O in Ar does not depend on the gas flow. This supports the idea of NO$_2$, and not N$_2$O, as an intermediate.

The hypothesis is that NO$_2$ is formed catalytically from NO, as described in Eq. 7, where LSM acts as a heterogeneous catalyst; afterward, the electrode reacts electrochemically with NO$_2$.

\[ \text{NO} + \text{LSM} \rightarrow \text{NO}_2 + \text{reduced LSM} \quad [7] \]

The LF arc is also seen in the spectra for cells in 1% NO$_2$ in Ar at 500 and 600°C, but it is much smaller than in the spectra for cells in NO, which corresponds well with the higher concentration of NO$_2$. Also, the arc does not increase with decreasing temperature for electrodes in NO$_2$ in Ar, which is expected as the actual concentration of NO$_2$ increases at lower temperatures.

The impedance plots for cells in an atmosphere of NO and O$_2$ in Ar also include a small LF arc at 600 and 500°C, and the EC values were in the range of the ones for the large NO LF arc for all the electrodes. Again, some NO$_2$ must be present due to the equilibrium between NO, O$_2$, and NO$_2$.

These results indicate that NO does not directly react electrochemically with the electrode around OCV but only indirectly via the intermediate. If NO reacts electrochemically with the electrodes, then the reaction has a much higher resistance than the reaction proceeding via an intermediate. But if the $R$ value of this process is much larger than that of the reaction with the intermediate, then it is not visible in the impedance spectra, as it mainly reflects the path of the equivalent circuit with the lowest overall resistance.

The NO$_2$ formed is quickly flushed away at the high flow rate, while at the low flow rate, the concentration of NO$_2$ close to the electrodes is higher. This could explain why the resistance of the LF arc is higher at high flow rates than at low flow rates.

When NO$_2$ is formed from NO on the perovskite and O$_2$ is not present in the atmosphere, then the perovskite must slowly become understoichiometric with respect to oxygen (see Eq. 7), and its ability to form NO$_2$ should decrease in time. This is illustrated in Fig. 14 where the resistance of the LF arc has clearly increased after 5 days in a NO-containing atmosphere. But even after 5 days, the presence of the arc means that NO$_2$ is still being formed. This suggests that some other species than the perovskite is being reduced, and in this system, the only other candidate would be the formation of N$_2$O from NO. An equilibrium such as that in Eq. 8 could be formed.

\[ 3\text{NO} \rightarrow \text{N}_2\text{O} + \text{NO}_2 \quad [8] \]

O$_2$ could also be a candidate for the component, which causes the LF conversion arc due to a low concentration in case a small leak was present in the setup. O$_2$ is not supposed to be present in the 1% NO in Ar atmosphere, as the setup has been leak tested before experiments. But this could explain that $R_p$ increases with flow rate; the higher the flow rate, the less effect a possible leak would have.

The LF arc, however, has also been identified in the spectra for electrodes in 0.75% NO + 5% O$_2$ in Ar, and as there is no lack of O$_2$ in this atmosphere, a diffusion arc due to lack of O$_2$ should be unlikely. Furthermore, the size of the LF arc depends quite strongly on the type of LSM–doped ceria, which may be explained by significant differences between the heterogeneous catalytic activity for the NO$_2$ forming processes.

**Temperature dependence.**—The electrodes had a much lower $R_p$ for 1% NO or NO$_2$ in Ar than for air in the 300–400°C range. The $R_p$ for the electrodes in air at 600°C was lower than 1% NO in Ar and similar to 1% NO$_2$ in Ar, but the activation energy for $R_p$ in air was larger than for 1% NO or NO$_2$ in Ar for nearly all the electrodes examined; the only exception being the LSM50/CPO10 electrodes, which had a larger $E_a$ for 1% NO$_2$ in Ar than for air.

As the actual temperature in the exhaust of a diesel engine is in the region of 200–300°C, it is optimal that the electrodes tested have lower resistances for NO$_2$ than for air in the low temperature range.

The apparent $E_a$ for electrodes in 1% NO in Ar was much lower than for air; this is mostly due to the large LF arc dominating the spectra in NO at high temperatures. When the $E_a$ for the MF arc, type C, are compared, the values in air are still higher than that in 1% NO in Ar. Thus, the electrodes react more easily with the intermediate (or NO) at low temperatures than with O$_2$. This could be due to changes in the kinetics at lower temperature, as the LF arc cannot be identified in the impedance spectra at 300°C for electrodes in 1% NO in Ar. The low p$_O2$ pressure could also affect the electrodes.

**Addition of oxygen.**—When 5% O$_2$ was added to the atmosphere containing 0.75% NO in Ar, the $R_p$ either decreased (high temperatures) or did not increase nearly as much as could be expected when looking at the very high $R_p$ for air in the temperature range of 300–400°C. This can be interpreted as the oxygen did not inhibit the reaction between the electrodes and NO$_2$. The addition of oxygen decreases the $R_p$ compared to the situation when only NO and Ar are present at some temperatures, as seen in Fig. 15.

The LF arc, which is usually present in the impedance spectra recorded in the atmosphere containing NO, is very small or missing when 5% O$_2$ is present. The first part of the impedance spectra for LSM electrodes in 1% NO in Ar and in 5% O$_2 + 0.75%$ NO$_2$ in Ar are similar (see Fig. 15). The lack of the LF arc could be explained by the presence of NO$_2$ from the reaction between O$_2$ and NO.

An alternative explanation could be that the electrodes become more efficient at reducing O$_2$, when NO are present, due to the formation of a more reactive oxygen surface species from the reaction between NO and O$_2$, as suggested by Reinhardt et al. 2

**Doping with Pr.**—The LF arc in NO was larger for the electrodes containing CPO, and the EC was higher compared to the LSM15CGO10 electrodes, shifting the LF arc to even lower fre-
quencies. The summit frequency of the LF arc at 600°C for CPO-containing electrodes was around 5 mHz, while it was around 250 mHz for the LSm50/CGo10 electrodes. This shift to higher capacitance (Table II) must be related to the doping of ceria with Pr. The Pr ions can change the oxidation state between 3+ and 4+ much easier than Ce and Gd. Thus, the higher capacitance may come from charge storage in the Pr ions. This corresponds well with the LSm50/CPo20 having higher capacitances than the LSm50/CPo10 (see Table II), which contains only half the amount of Pr ions.

The LSm50/CPo20 electrodes generally have lower R around NO in atmospheres containing NO compared to the LSM15/CGO10 electrodes and also had a higher apparent Ea in NO and the highest E in air. This is due to higher R of the CPO-containing electrodes at high temperatures, where R dominates the spectra. The LSm50/CPo10 and LSm50/CPo20 electrodes must have less catalytic activity for producing NO2 compared to the LSm15/CGO10 electrodes at the high temperatures, as the LF arc is linked to the concentration of the intermediate. This can be caused by the CPO doping, but the variation in Sr content between LSm15 and LSm50 might also play a role.

Conclusion

All the impedance data were fitted with equivalent circuits, and between two and four arcs were identified in each impedance spectrum. Changing the atmosphere and temperature had a large impact on the appearance of the impedance spectra and on the size of the R. The electrodes were more active in atmospheres containing NO or NO in air, as the R was much smaller than that in air. The addition of 5% O2 lowered the R for electrodes in 1% NO in Ar.

The electrodes had a lower apparent E in NO-containing atmosphere than in air. The electrodes containing CPO had a lower E in a NO-containing atmosphere than the LSm15/CGO10 electrodes. Further, the electrodes of type LSm50/CPo20 had the lowest R when the atmosphere was 1% NO or NO in Ar at the temperatures of 300–400°C.

The resistance was significantly lower in 1% NO in Ar than for 1% NO in Ar at higher temperatures, mostly due to the large LF arc seen in the NO impedance spectrum for all types of electrodes. The same type of arc was also seen in the spectra for electrodes in NO + O2 and NO2. This arc is a type of conversion arc caused by a reaction, which is limited by a low concentration of intermediate reactants. The electrodes seem to be relatively inactive toward NO around OCV when no O2 or NO2 is present at high temperatures. The intermediate is probably NO, as the electrodes have much lower R in an atmosphere containing NO2. Therefore, the reaction causing the LF arc likely takes place through the following reaction steps: First, the intermediate, NO2, is formed catalytically from NO by LSm, and then the electrode reacts electrochemically with NO2.

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