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Physical Properties of Mixed Conductor
Solid Oxide Fuel Cell Anodes of Doped CeO₂

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ABSTRACT

Samples of CeO₂ doped with oxides such as CaO and Gd₂O₃ were prepared. Their conductivities and expansions on reduction were measured at 1000°C, and the thermal expansion coefficients in the range 50 to 1000°C were determined. The ionic and electronic conductivity were derived from curves of total conductivity vs. oxygen partial pressure. For both types of conductivity a dependence on dopant valency was observed. The electronic conductivity was independent of dopant radius in contrast to the ionic which was highly dependent. These measured physical properties are compared with the ideal requirements for solid oxide fuel cell anodes. Not all requirements are fulfilled. Measures to compensate for this are discussed.

Mixed ionic and electronic conductors (MIEC) seem to be the best type of electrode materials for electrochemical devices such as solid oxide fuel cells (SOFC) and electrolyzers. However, until now most developers of SOFC do not use effective MIEC electrodes. The reason for this is that it is not sufficient for a material to be an MIEC. For an MIEC to act as both an efficient electrode and current collector several requirements must be fulfilled: (i) ionic conductivity, \( \sigma_\text{i} \geq 0.1 \text{ S/cm} \) and electronic conductivity, \( \sigma_\text{e} \geq 100 \text{ S/cm} \) at operating conditions; (ii) dimensional and thermodynamic stability over wide ranges of oxygen partial pressure and temperature; (iii) good thermal expansion coefficient match with the electrolyte; (iv) chemical compatibility with the electrolyte during operation and fabrication; and (v) high electrocatalytic activity for oxygen reduction and fuel oxidation for cathode and anode, respectively.

Pure CeO₂ samples were prepared by uniaxial pressing of commercial powder (REACTON 99.9% CeO₂, the impurities being mainly other rare earths). CeO₂ samples doped with Gd₂O₃, Sm₂O₃, Y₂O₃, CaO, Pr₂O₃, Sc₂O₃, etc. were prepared from Ce(NO₃)₃ · 6H₂O, Gd(CH₃COO)₃, Sm(NO₃)₃, Y(CH₃COO)₃, Ca(NO₃)₂, Pr(NO₃)₃, or Sc(CH₃COO)₃ by a process similar to that of Pechini. The purity of the Ce(NO₃)₃ · 6H₂O was better than 98.5% and of other salts better than 99.9%. In the cerium compound the impurities were stated to be mainly other rare earths (La < 0.2%, Er < 0.2%, others < 0.04%). The level of impurities such as Fe and Pb were below 20 ppm. The sample doped with V₂O₃ was prepared directly from the oxides by a solid-state reaction route. All samples prepared according to the Pechini method plus the pure CeO₂ were sintered at 1600°C for 2 h, the rest were sintered at 1600°C for 12 h. All samples had densities close to 90% of the theoretical value except the pure ceria (74%). In all cases the measured conductivities were corrected for the porosity by dividing with the actual density and multiplying with the theoretical.

This correction procedure probably gives values slightly too low. It was chosen in spite of this for two reasons; (i) most of the literature data available for comparison are stated to be corrected this way and (ii) to make a theoretically well-founded correction we must make a careful characterization of the porosity structure. This takes a major effort and probably only changes the conductivity values by a few percent. Brugner and Blumenthal reported a comparison of conductivity values for a single-crystal CeO₂ and sintered CeO₂ samples 70 and 85% dense, and found excellent agreement using this simple correction procedure.

The samples were examined by x-ray diffraction (XRD) and with one exception consisted of a single-phase fluorite structure. Traces of undissolved Sc₂O₃ were detected in the compound with the nominal formula Ce₀.995Sc₀.005O₁.95. The conductivity measurements were carried out in a furnace where the oxygen partial pressure was controlled by well-defined mixtures of air, Ar, CO₂, CO, H₂O, and H₂. In all cases the oxygen potential was measured with an oxygen sensor and showed good agreement with values derived from thermodynamic data. The measurements were performed using a two-electrode setup and a computer-controlled Solartron 1260 impedance analyzer similar to the procedure described by Bentzen et al. The resistances of the leads were measured frequently by short-circuiting the sample holder. The resistances of leads were in the range of 3.8 to 4.2 kΩ. Changes in this resistance were observed only after occasional replacement of leads or electrodes. The uncertainty of the measured resistances of the

* Electrochemical Society Active Member.
samples were 0.05 \Omega resulting in a maximum uncertainty of 5% for the specific conductivity. The temperature was measured in all cases to 1000 ± 3°C.

The measurements on expansion on reductions and of the thermal expansion coefficients were performed according to previously described procedures.⁴

Results and Discussion

The measured impedances were plotted in the complex plane and the contributions from lattice, grain boundaries, and electrodes were separated using LEVM which is a PC-based fitting program developed by Macdonald.⁴

Examples of impedance plots for the sample Ce₀.₈Ca₀₁₂O₁₈ obtained at different \( P_{O_2} \) are given in Fig. 1, 2, and 3. The vertical part below the real axis in all the plots is due to inductive elements in the experimental setup. Figure 1 shows an impedance spectrum measured in air. How the response is separated into contributions from lattice, grain boundaries, and electrodes is indicated. The conductivity measured in air is assumed to be entirely ionic. The spectrum in Fig. 2 is measured while the sample was exposed to an atmosphere of CO and \( \text{CO}_2 \), \( P_{O_2} = 4.5 \times 10^{-1} \) atm. Besides the inductance Fig. 2 shows only a Warburg type of electrode response. This means that the grain boundary resistance becomes insignificant when the atmosphere is sufficiently reducing. This is attributed to the introduction of electronic carriers short-circuiting the grain boundaries. Also, this electronic conductivity decreases the lattice resistance as revealed by comparing \( R_1 \) of Fig. 2 with \( R_1 \) of Fig. 1. In Fig. 3 the atmosphere is \( \text{H}_2 + 3\% \text{H}_2\text{O}, \ P_{O_2} = 4.5 \times 10^{-18} \) atm. In this case substantial electronic conductivity is introduced and the impedance spectrum is reduced to a single dot; no capacitive elements are observed and no change in the real part is observed when varying the frequency from 100 kHz to 0.1 Hz. This is better illustrated by the Bode plot in Fig. 4 where both real part and imaginary part are given as a function of logarithm of frequency.

All the conductivities reported from this work are lattice conductivities, which supposedly are material properties unaffected by the preparation route. The literature data given, however, are total conductivities including the grain boundary resistance because pure lattice conductivity data at 1000°C are not reported. In this work all measured grain boundary resistances were less than 10% of the total resistance. They are not reported because the values were not revealing any clear trends. It has been reported that grain boundary resistance in fluorite oxides ion conductors in general is dependent on grain size, porosity, and trace impurities.⁵ A careful control of these parameters was not attempted here.

**Total conductivity.**—Using the Kröger-Vink notation the reduction of \( \text{CeO}_2 \) may be written as

\[
\text{O}_2^0 \rightarrow \text{Ce}^{+3} + \text{V}_{\text{Ce}}^{2+} + 3 \text{O}^{-}\]

\[\text{[1]}\]

\( \text{O}_2^0 \) is an \( \text{O}^{-} \) ion on its normal site in the \( \text{CeO}_2 \) lattice (regarded as neutral) and \( \text{V}_{\text{Ce}}^{2+} \) is a double positively charged vacancy.

The electronic conductivity is induced when the material is reduced as given in Eq. 1. Additional oxygen is removed from the material when dopants of valence lower than +4 are incorporated in the lattice. This happens according to Eq. 2

\[
\text{Gd}_2\text{O}_3 \rightarrow 2\text{Gd}_{\text{Ce}}^{+3} + \text{V}_{\text{Ce}}^{2+} + 3 \text{O}_2^0
\]

The vacancies that are formed as a consequence of the doping shift the reaction in Eq. 1 to the left, with a decrease in electron concentration and \( \sigma \), as the result.

An overview of the differences between \( \text{Gd}_2\text{O}_3 \) and \( \text{CaO} \)-doped \( \text{CeO}_2 \) is given in Fig. 5, 6, and 7. Figure 5 shows the total conductivity vs. \(-\log P_{O_2}\) for different levels of gadolinia doping. At high \( P_{O_2} \) (oxygen partial pressure) the conductivity is only slightly affected by changes in \( P_{O_2} \). Under more reducing conditions the conductivity increases and eventually becomes constant or goes through a maxi-

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**Fig. 1.** A raw impedance plot for the sample Ce₀.₈Ca₀₁₂O₁₈ measured in air at 1000°C. \( R_1 \) is equal to the sample lattice resistance plus the lead resistance, \( R_2 - R_1 \) is the grain boundary resistance, and \( R_3 - R_2 \) is the electrode resistance. The lead resistance is measured in a separate experiment.

**Fig. 2.** Impedance plot for the sample of Fig. 1 measured in \( \text{CO}/\text{CO}_2, P_{O_2} = 4.5 \times 10^{-11} \) atm 1000°C.

**Fig. 3.** Impedance plot for the sample of Fig. 1 measured in \( \text{H}_2 + 3\% \text{H}_2\text{O}, P_{O_2} = 4.5 \times 10^{-18} \) atm 1000°C.
When the dopant concentration is increased the resistance to reduction increases. The result of this is a shift toward lower \( p_{02} \) values for the same conductivity.

Figure 4 shows the total lattice conductivity vs. \(-\log p_{02}\) for samples with composition \( \text{Ce}_0.8\text{Gd}_0.2\text{O}_{1.8} \) and \( \text{Ce}_0.8\text{Ca}_0.2\text{O}_{1.8} \). \( \text{Ce}_0.8\text{Gd}_0.2\text{O}_{1.8} \) has a slightly higher ionic conductivity, but a significantly lower electronic conductivity.

Figure 5 shows the total lattice conductivity vs. \(-\log p_{02}\) for samples with composition \( \text{Ce}_0.8\text{Gd}_0.2\text{O}_{1.8} \) and \( \text{Ce}_0.8\text{Ca}_0.2\text{O}_{1.8} \). The difference in electronic conductivity has been further increased compared to the results in Fig. 4 and the ionic conductivity of the calcia-doped sample is now clearly highest.

**Ionic conductivity in air.** For all samples including pure \( \text{CeO}_2 \), the conductivity measured in air is regarded as being ionic, the electronic conductivity contribution being negligible. This is assumed to be a reasonable approximation as the impedance plots clearly showed the presence of semiarcs indicating that the capacitance of the grain boundaries was not short-circuited. All ionic conductivities reported in the following are lattice conductivities obtained from measurements performed in air.

The ionic lattice conductivity, \( \sigma_{\text{i,l}} \), at 1000°C for \( \text{CeO}_2 \) doped with either \( \text{Gd}_2\text{O}_3 \) or \( \text{CaO} \) is shown in Fig. 8. \( \sigma_{\text{i,l}} \) is plotted as a function of the nominal vacancy concentration, \( \left[V_{\text{o}}^+\right] \), which is the concentration of vacancies necessary to obtain electrical neutrality in the lattice, assuming unassociated double-charged vacancies.

Five different concentrations of \( \text{Gd}_2\text{O}_3 \) have been investigated including pure \( \text{CeO}_2 \). The highest ionic conductivity found was 0.19 S/cm, measured for Ce\(_{0.8}\)Gd\(_{0.2}\)O\(_{1.8}\). This is in reasonable agreement with literature data\(^{16-18} \) regarding the concentration as well as the conductivity. As the literature data include grain boundary resistance it indicates that the grain boundary resistance is relatively low in all cases at 1000°C. The values measured within this work also confirm literature data on other dopant concentrations [4, 6, 8, and 40 atom percent (a/o)].\(^{16-18} \)

Doping with \( \text{CaO} \) gives lower values of \( \sigma_{\text{i,l}} \) than \( \text{Gd}_2\text{O}_3 \) in the concentration range from 0 to 10 a/o Ca. The maximum \( \sigma_{\text{i,l}} \) was 0.19 S/cm, measured for Ce\(_{0.6}\)Ca\(_{0.4}\)O\(_{1.8}\). The values obtained here are, with one exception, very close to the results of Blumenthal et al.\(^{19} \) and Arai et al.\(^{20} \) The sample doped with 20% \( \text{CaO} \) also had an ionic conductivity of 0.19 S/cm. This is higher than found by Arai et al.\(^{20} \) (0.16 S/cm).

Three main parameters determine the ionic lattice conductivity \( \sigma_{\text{i,l}} \): temperature, dopant concentration (concentration of oxide ion vacancies), and dopant metal ion radius. As the literature data include grain boundaries, an indication that the correlation between \( \Delta r \) and \( \sigma_{\text{i,l}} \) varies...
with the valency of the dopant ion. The figure implies that $\sigma_1$ is more affected by ion radius of trivalent dopants than by the divalent. The two curves have been drawn to guide the eye, the experimental data are too few to make any definite conclusions on this matter.

The implication of Fig. 9 is that the best trivalent dopant ion is Tb$^{3+}$ for which $\Delta r = 0.002 \text{ Å}$ but only marginally better than Gd$^{3+}$ with $\Delta r = 0.015 \text{ Å}$. Gd$_2$O$_3$ was chosen for the detailed investigation because Gd$_2$O$_3$ is considerably cheaper than Tb$_2$O$_3$.

**Ionic conductivity in reducing atmosphere.**—In the literature, $\sigma_1$ is often regarded as constant, independent of $P_{O_2}$. This however is not fully true. As CeO$_2$ is reduced according to Eq. 1 the concentration of vacancies is increased which leads to a change in $\sigma_1$. The maximum in $\sigma_1$ is probably obtained close to $[V_0^-] = 5\%$ of anion sites. Direct measurement of $\sigma_1$ has not been possible under reducing conditions, but an estimate has been obtained using the data of Zachau-Christianensen et al. where the oxygen stoichiometry has been determined for pure and Gd-doped ceria as a function of $P_{O_2}$. Direct measurement of $\sigma_1$ has not been possible under reducing conditions, but an estimate has been obtained using the data of Zachau-Christianensen et al. where the oxygen stoichiometry has been determined for pure and Gd-doped ceria as a function of $P_{O_2}$. Direct measurement of $\sigma_1$ has not been possible under reducing conditions, but an estimate has been obtained using the data of Zachau-Christianensen et al. where the oxygen stoichiometry has been determined for pure and Gd-doped ceria as a function of $P_{O_2}$.

$\sigma_1$ is expected to be affected by the reduction process in the same way as when the concentration of trivalent dopant is increased. In this case the dopant is Ce$^{3+}$.

The ionic radius of Ce$^{3+}$ is close to that of La$^{3+}$ (1.143 and 1.16 Å, respectively). Knowing that the ionic radius of the dopant material is an important parameter for the value of $\sigma_1$, it has been assumed that $\sigma_i$ (measured in air) for the compound Ce$_{1-2\%}$La$_{2\%}$O$_{2-\%}$ is a good estimate for $\sigma_1$ in CeO$_{2-x}$ (alternatively written as Ce$_{1-2\%}$Ce$_{2\%}$O$_{2-\%}$). Combining the stoichiometry measurements of Zachau-Christianensen with conductivity measurements on Ce$_{1-2\%}$La$_{2\%}$O$_{2-\%}$, a curve showing $\log(\sigma_i)$ vs. $-\log P_{O_2}$ for CeO$_{2-x}$ has been constructed (Fig. 10). The curve goes through a maximum with the highest $\sigma_i = 0.07 \text{ S/cm}$ obtained at $P_{O_2} = 10^{-18}\text{ atm}$ and $[V_0^-] = 5.3\%$ of anion sites. The maximum $\sigma_i$ obtained from Fig. 10 is approximately 18 times higher than $\sigma_i$ measured in air, the latter being controlled by the impurity level of lower valent dopants.

In the case of the doped samples the correlation between $\sigma_i$ and $P_{O_2}$ depends on the dopant concentration, e.g., Ce$_{0.8}$Gd$_{0.2}$O$_{1.8}$, where the optimum concentration of vacancies already has been achieved, $\sigma_i$ probably decreases when $P_{O_2}$ is lowered.

Compared to the electronic conductivity obtained for oxygen partial pressures lower than $10^{-4} \text{ atm}$ the change in $\sigma_i$ caused by reduction is insignificant. For pure CeO$_2$...
Electronic conductivity.—Fundamental studies on the n-type conduction in CeO$_2-x$ have been reported in the literature. It is generally agreed that the conduction occurs via a small polaron hopping mechanism, but there is disagreement in the literature about how $\sigma_n$ depends on dopant concentration. Ivers-Tiffee and Künstner and Ivers-Tiffee and Oel$^{26}$ have examined the electronic conductivity of samples with the composition Ce$_{1-x}$M$_x$O$_{2-x/2}$ ($M = \text{Gd, Er, Nd}$ and $x = 0$ to 0.16) in the temperature range from 700 to 900$^\circ$C, and have found that $\sigma_n$ is not affected by any changes in dopant material or concentration. In contradiction to this, El Adham$^{27}$ has found a slope of $\log \sigma_n$ vs. log $x$ to be approximately $-1/2$ for $0 < x < 0.15$ at 783$^\circ$C and $p_{O_2} = 1.5 \times 10^{-13}$ atm, i.e., the electronic conductivity decreases with increasing concentration of dopants with valence lower than +4. The same slope has been obtained here at 1000$^\circ$C and $p_{O_2} = 10^{-14}$ atm for $0.045 < x < 0.1$. For values of $x \geq 0.2$ or $p_{O_2} \leq 10^{-12}$ atm other correlations have been found, but in all cases the results of the present work (shown in Fig. 11, 12, and 13) confirm clearly that $\sigma_n$ decreases when CeO$_2$ is doped with lower valent cations.

Figure 11 shows the electronic conductivity, $\sigma_n$, vs. $-\log p_{O_2}$ for various dopants in varying concentrations. $\sigma_n$ is simply found as $\sigma_n = \sigma - \sigma_i$, where $\sigma_{tot}$ is the total conductivity and $\sigma_i$ is the ionic lattice conductivity measured in air. Considering the arguments given in the section Ionic Conductivity in Reducing Atmosphere, this approximation seems reasonable.

For undoped CeO$_2$, it can be shown$^{28}$ that the concentration of electronic charge carriers, $n$, is correlated to $p_{O_2}$: $n \propto p_{O_2}^{-4}$ for small departures from stoichiometry, and $n \propto p_{O_2}^{-1}$ for large departures from stoichiometry. In the case of the doped samples the theoretical correlation is: $n \propto p_{O_2}^{-4}$.

The curves for the doped samples (Fig. 11) show that the slope is close to the theoretical value 0.25 and that it is virtually unaffected by both the kind of dopant and concentration. For pure CeO$_2$ the slope is approximately 0.2 indicating a transition state between the two theoretical slopes. The observed decrease in conductivity, compared to pure CeO$_2$, is almost the same when doping to equal concentrations of Gd$_2$O$_3$ and Pr$_2$O$_3$ or Gd$_2$O$_3$ and Sm$_2$O$_3$. It appears that $\sigma_n$ is not affected by the choice of dopant as long as the valence of the dopant material remains the same (+3 in this case). Doping with the divalent CaO also causes a lowering of $\sigma_n$, but not as much as the trivalent lanthanides do.

Doping with the pentavalent V$_2$O$_5$ shows a slight increase in $\sigma_n$ compared to pure CeO$_2$. This can be attributed to the introduction of cation vacancies. These react with oxide vacancies with the result that Eq. 1 is shifted to the right. The consequence of this is a decrease in $\sigma_n$ and an increase in $\sigma_e$. Similar observations have been reported in the literature.$^{29,30}$

Figure 12 and 13 compare $\sigma_n$ at $p_{O_2} = 10^{-15}$ atm for samples doped with Gd$_2$O$_3$ or CaO. In Fig. 12 $\sigma_n$ is plotted vs. $y$ in Ce$_{1-x}$Gd$_x$O$_{2-y}$ and Ce$_{1-x}$Ca$_x$O$_{2-y}$, whereas in Fig. 13 $\sigma_n$ is plotted vs. the dopant concentration in atom fraction. Figure 12 is shown to compare compounds which have equal nominal concentrations of defects in the anion lattice, e.g., Ce$_{0.8}$Gd$_{0.2}$O$_{1.8}$ and Ce$_{0.8}$Ca$_{0.2}$O$_{1.8}$. The formulas in Fig. 12 do not represent the true stoichiometry at $p_{O_2} = 10^{-15}$ atm. Due to the reducing atmosphere additional oxygen has been removed from the lattice. To find the exact extent of this reduction we must measure the stoichiometry as in the work of Zachau-Christiansen et al.$^{23}$ or by thermogravimetry. One of the main findings of Ref. 23 is that for a given $p_{O_2}$ value the oxygen stoichiometry, e.g., at $p_{O_2} = 10^{-15}$ atm is independent of the Gd concentration up to 40 a/o Gd. In the $p_{O_2}$ interval from $10^{-14}$ to $10^{-9}$ atm the oxide vacancy concentration is even smaller.

which has the ionic conductivity most sensitive to changes in $p_{O_2}$. $\sigma_i$ introduced by the reduction is less than 3% of the total conductivity at $p_{O_2} = 10^{-9}$ atm. At lower values of $p_{O_2}$ the contribution is even smaller.

Electronic conductivity.—Fundamental studies on the n-type conduction in CeO$_2-x$ have been reported in the literature. It is generally agreed that the conduction occurs via a small polaron hopping mechanism, but there is disagreement in the literature about how $\sigma_n$ depends on dopant concentration. Ivers-Tiffee and Künstner$^{26}$ and Ivers-Tiffee and Oel$^{27}$ have examined the electronic conductivity of samples with the composition Ce$_{1-x}$M$_x$O$_{2-x/2}$ ($M = \text{Gd, Er, Nd}$ and $x = 0$ to 0.16) in the temperature range from 700 to 900$^\circ$C, and have found that $\sigma_n$ is not affected by any changes in dopant material or concentration. In contradiction to this, El Adham$^{28}$ has found a slope of $\log \sigma_n$ vs. log $x$ to be approximately $-1/2$ for $0 < x < 0.15$ at 783$^\circ$C and $p_{O_2} = 1.5 \times 10^{-13}$ atm, i.e., the electronic conductivity decreases with increasing concentration of dopants with valence lower than +4. The same slope has been obtained here at 1000$^\circ$C and $p_{O_2} = 10^{-14}$ atm for $0.045 < x < 0.1$. For values of $x \geq 0.2$ or $p_{O_2} \leq 10^{-12}$ atm other correlations have been found, but in all cases the results of the present work (shown in Fig. 11, 12, and 13) confirm clearly that $\sigma_n$ decreases when CeO$_2$ is doped with lower valent cations.

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Figure 12 and 13 compare $\sigma_n$ at $p_{O_2} = 10^{-15}$ atm for samples doped with Gd$_2$O$_3$ or CaO. In Fig. 12 $\sigma_n$ is plotted vs. $y$ in Ce$_{1-x}$Gd$_x$O$_{2-y}$ and Ce$_{1-x}$Ca$_x$O$_{2-y}$, whereas in Fig. 13 $\sigma_n$ is plotted vs. the dopant concentration in atom fraction. Figure 12 is shown to compare compounds which have equal nominal concentrations of defects in the anion lattice, e.g., Ce$_{0.8}$Gd$_{0.2}$O$_{1.8}$ and Ce$_{0.8}$Ca$_{0.2}$O$_{1.8}$. The formulas in Fig. 12 do not represent the true stoichiometry at $p_{O_2} = 10^{-15}$ atm. Due to the reducing atmosphere additional oxygen has been removed from the lattice. To find the exact extent of this reduction we must measure the stoichiometry as in the work of Zachau-Christiansen et al.$^{23}$ or by thermogravimetry. One of the main findings of Ref. 23 is that for a given $p_{O_2}$ value the oxygen stoichiometry, e.g., at $p_{O_2} = 10^{-15}$ atm is independent of the Gd concentration up to 40 a/o Gd. In the $p_{O_2}$ interval from $10^{-14}$ to $10^{-9}$ atm the oxide vacancy concentration is even smaller.
centrations seem to be a function of the oxygen partial pressure only. This is valid for oxide vacancy concentrations at up to 10% of the oxide sites irrespective of whether the dopant is Gd$^{3+}$ or Ce$^{4+}$. If this is assumed to be also valid if Ca is the dopant then, according to Eq. 1, the electron concentration, $n$, should be the same for the same $y$-value in Fig. 12. The electronic mobility is defined by

$$\sigma_e = ne \mu_e$$  \hspace{1cm} [3]$$

where $e$ is the elementary charge, and $\mu_e$ the electron mobility. In Fig. 12 $\sigma_e$ is considerably higher for the samples doped with CaO. This implies that it is not the extent of the reduction which alone determines $\sigma_e$. If the electron concentration, $n$, is assumed to be equal for Ce$_{0.8}$Gd$_{0.2}$O$_{1.9}$ and Ce$_{0.8}$Ca$_{0.2}$O$_{1.9}$ at $P_{O_2} = 10^{-15}$ atm then the only explanation for the difference in $\sigma_e$ is a considerable variation in the electronic mobility. The electronic mobility in small polaron conductors is described by Tallur and Nowick$^{22}$ as having the following form

$$\mu_e = \left( \frac{[Ce^0]}{[Ce^{+}]} \right) \cdot \exp \left( \frac{-E_H}{kT} \right)$$  \hspace{1cm} [4]$$

where $a$ is the jump distance, $v_0$ the attempt frequency, $E_H$ the hopping energy, and $k$ is the Boltzmann constant.

An important variable in the mobility is $[Ce^0]$, i.e., the concentration of sites where the electron can jump. If some $Ce^0$ sites are exchanged with a fixed valence ion like Gd$^{3+}$ or Ca$^{2+}$ fewer sites are available for the mobile electrons, thereby reducing the mobility and hence $\sigma_e$. For the samples compared in Fig. 12, $[Ce^0]$ is only half the value of $[Gd^3+]$ which partly explains the difference in $\sigma_e$. In Fig. 13 $\sigma_e$ is compared for equal concentrations of dopant metal ions. In this case the two curves appear almost merging with a tendency towards CaO giving a higher value of $\sigma_e$.

Were $\sigma_e$ controlled solely by $[Vo^+]$ and dopant metal ion concentration, the samples doped with Gd$_2$O$_3$ would have exhibited the highest conductivity in Fig. 13. Apparently other parameters have a determining influence on $\sigma_e$ with the consequence that calcium-doped samples obtain a higher $\sigma_e$ than gadolinia-doped. This may be because the vacancy-dopant associates in the Ca case (Ca$^{2+}$ - Vo$^{+}$) are neutral while in the Gd case (Gd$^{3+}$ - Vo$^{+}$) they are positively charged and this may decrease the electron mobility.

Table I compares $\sigma_e$ at $P_{O_2} = 10^{-15}$ atm with the ion radii of different dopants. Again as in Fig. 8 and 12 compounds with the same nominal vacancy concentration are compared. The values indicate that the ion radii do not influence the size of $\sigma_e$.

**Table I. Electronic conductivity, $\sigma_e$, and ionic radii for dopant material.**

<table>
<thead>
<tr>
<th>Sample</th>
<th>$\sigma_e$ (S cm$^{-1}$)</th>
<th>Ionic radius of dopant (Å)</th>
<th>$\Delta r^+$ (Å)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ce$<em>{0.8}$Pr$</em>{0.2}$O$_{1.9}$</td>
<td>1.2</td>
<td>1.126</td>
<td>0.088</td>
</tr>
<tr>
<td>Ce$<em>{0.8}$Gd$</em>{0.2}$O$_{1.9}$</td>
<td>1.44</td>
<td>1.053</td>
<td>0.015</td>
</tr>
<tr>
<td>Ce$<em>{0.8}$Ca$</em>{0.2}$O$_{1.9}$</td>
<td>2.38</td>
<td>1.120</td>
<td>0.014</td>
</tr>
<tr>
<td>Ce$<em>{0.8}$Sm$</em>{0.2}$O$_{1.9}$</td>
<td>0.30</td>
<td>1.079</td>
<td>0.041</td>
</tr>
<tr>
<td>Ce$<em>{0.8}$La$</em>{0.2}$O$_{1.9}$</td>
<td>0.33</td>
<td>1.053</td>
<td>0.015</td>
</tr>
<tr>
<td>Ce$<em>{0.8}$Gd$</em>{0.2}$O$_{1.9}$</td>
<td>0.33</td>
<td>1.160</td>
<td>0.122</td>
</tr>
<tr>
<td>Ce$<em>{0.8}$La$</em>{0.2}$O$_{1.9}$</td>
<td>1.6</td>
<td>1.12</td>
<td>0.014</td>
</tr>
</tbody>
</table>

$P_{O_2} = 10^{-15}$ atm, $[Vo^+]$ = 5 and 10%.

The ionic radii are those given by Shannon$^{22}$ for a coordination number of 8.

For pure and 5 doped cerias. The clear trend is that the higher the degree of doping with two- or three-valent cations, the less the relative expansion associated with the reduction of the samples. This is in agreement with the equilibria given by Eq. 1 and 2.

A considerable scatter is seen in 20% Ca in Fig. 14. A possible explanation may be that this composition is not stable in reduced condition over periods of time of 20 to 40 h, i.e., some of the Ca is precipitated in domains with some extra ordering of Ca$^2+$ and V$^{2+}$ as compared to the oxidized state. This implies that the actual expansion is dependent on the hold time at a given condition. This is being investigated further. Figure 14 also reveals that even in case of as high a degree of doping as 40% Gd or 50% Er there is still an appreciable expansion below $-1$ V.

The thermal expansion coefficients (TEC) of the samples in Fig. 14 are given in Table II. The ceria TECs are in all cases higher than for yttria-stabilized zirconia (YSZ).

**Extent of matching of the SOFC anode requirements.—** The experimental results show that the requirement of an electronic conductivity of $\sigma_e \geq 0.1$ S/cm is easily met. Otherwise with the electronic conductivity. Irrespective of which kind and degree of dopant, $\sigma_e \geq 100$ S/cm never can be met for ceria-based material. So to use ceria as an anode a current collector with the required electronic conductivity must be implemented. A possible candidate for this may be porous chromium steel of a composition similar to the metallic SOFC interconnector plate reported by Drenckhahn and Vollmar$^{23}$.

- The results (Fig. 14) show that we must substitute about half the Ce atoms with Gd or similar rare-earth element to obtain a reasonable dimensional stability. In doping with Ca there may be a problem with both dimensional and thermodynamic stability. It is probably not possible to avoid an expansion of at least 0.3%. Whether this is allow-

**Table II. TEC for various doped cerias in air in the interval 50 to 1000°C.**

<table>
<thead>
<tr>
<th>Composition</th>
<th>TEC ($10^{-6}$ K$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CeO$_2$</td>
<td>12.3</td>
</tr>
<tr>
<td>Ce$<em>{0.8}$Gd$</em>{0.2}$O$_{1.9}$</td>
<td>12.5</td>
</tr>
<tr>
<td>Ce$<em>{0.8}$Er$</em>{0.2}$O$_{1.9}$</td>
<td>12.1</td>
</tr>
<tr>
<td>Ce$<em>{0.8}$Ca$</em>{0.2}$O$_{1.9}$</td>
<td>12.8</td>
</tr>
<tr>
<td>Ce$<em>{0.8}$La$</em>{0.2}$O$_{1.9}$</td>
<td>13.4</td>
</tr>
<tr>
<td>Ce$<em>{0.8}$Gd$</em>{0.2}$O$_{1.9}$</td>
<td>13.6</td>
</tr>
<tr>
<td>Zr$<em>{0.5}$Y$</em>{0.5}$O$_{1.95}$</td>
<td>10.8</td>
</tr>
</tbody>
</table>
able or not probably depends on the actual structure of the full cell stack. The TEC match with YSZ is believed to be acceptable at least for the heavily Gd- and Er-doped ceramics.

The chemical compatibility of CeO₂ with YSZ is not without problems as the two materials diffuse into each other at the sintering temperature which typically is about 1300°C or above. The CeO₂-YSZ solutions have considerably lower oxide ion conductivities than YSZ itself. At 1000°C Zr₈₅₋₀.₂₅Ce₀.₇₅O₁.₉₃ has a stable ion conductivity of about 0.12 S/cm while for YSZ mixed with various amounts of Ce⁴⁺ and Gd³⁺ was in the range of 0.02 to 0.06 S/cm. The same trend is seen in the work of Cales and Baumard. This means that during the fabrication process measures should be taken to avoid the interdiffusion, e.g., by using low temperature methods or by applying a suitable diffusion barrier onto the YSZ surface.

The requirement of high electrocatalytic activity seems to be fulfilled for oxidation of hydrogen, but still more work is needed to see if it can be made high enough for direct CH₄ oxidation.

Conclusion

For CeO₂-based anodes it seems that the best composition is one where 40 to 50% of the Ce⁴⁺ is substituted with three-valent rare-earth cations like Y³⁺, Gd³⁺ or similar rare-earth cation with slightly smaller ion radius.

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