

Proton-conducting oxides based on LaScO_3 : structure, properties and electrochemical applications. A focus review

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Solid state proton conductors are promising materials for various electrochemical applications. LaScO_3 -based oxides are representatives of the proton-conducting oxides with perovskite structure, alternative to conventional cerates and zirconates of alkaline-earth elements. These oxides exhibit a sufficient level of proton conductivity with a combination of good chemical stability in the H_2O and CO_2 -containing atmospheres. The current review is focused on summarizing and analyzing of the currently available data on LaScO_3 -based oxides. The peculiarities of crystal structure and proton defect formation, aspects of synthesis and obtaining dense ceramics, and electrical properties are provided. Additionally, the current state of applications in electrochemical devices of LaScO_3 -based oxides is briefly discussed.

keywords: LaScO_3 , proton-conducting oxide, electrical conductivity, perovskite, SOFC

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1. Introduction

Solid oxides with a perovskite structure attract the attention of researchers due to various possible applications [1–3]. One of them is solid oxide fuel cells - devices that convert chemical energy directly into electricity. A conventional SOFC consists of a solid electrolyte membrane with oxygen-ionic conductivity and two electrodes (anode and cathode) [4, 5]. To date, one of the main obstacles to the wide commercialization of SOFCs is their high working temperature (about 800°C), which leads to a high price for electricity. Therefore, there is a demand to develop new functional materials that can operate at reduced temperatures. This can be achieved by using solid state proton conductors (SSPC) as an electrolyte membrane in SOFC instead of

oxygen-ionic conductors. Since the activation energy of proton conductivity is lower than that of the oxygen-ionic, a sufficient level of conductivity can be achieved at lower temperatures (below 700°C), thus reducing the operating temperature of the electrochemical device [6, 7]. Iwahara et al. first reported proton conductivity in complex oxides in 1981 [8]. Since that time, a huge amount of various oxides have been studied considering the possibility of proton transport in their structure, e.g. with perovskite [9–13], pyrochlore [14–17], brownmillerite and layered structures [17–20]. The most well-studied oxides are materials based on cerates and zirconates of alkaline earth elements, presenting the class of $\text{A}^{2+}\text{B}^{4+}\text{O}_3$ perovskites. They usually exhibit a high level of proton conductivity, but suffer from low chemical stability and high grain boundary resistance [21, 22]. Another group of the oxides with perovskite structure has the common formula $\text{A}^{3+}\text{B}^{3+}\text{O}_3$, such as LaGaO_3 , LaInO_3 , LaScO_3 , LaAlO_3 , etc. [23–25]. Among them, LaScO_3 -based oxides were found to exhibit sufficient level of proton conductivity with the combination of good chemical

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stability in the H₂O and CO₂ - containing atmospheres [23]. Therefore, these oxides can be considered as promising electrolyte materials for SOFCs or other electrochemical devices. The purpose of this paper is to provide a brief overview of the current status of studies on LaScO₃ - based oxides and their electrochemical applications.

2. LaScO₃ - based oxides: synthesis, structure, water uptake

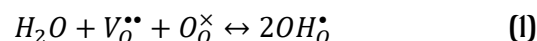
The most common way to obtain complex oxides is a solid state reaction technique. Using this method, LaScO₃ - based oxides were obtained in [25–28]. However, using this method, it is difficult to obtain dense ceramics even after long-term high-temperature sintering, and therefore, the application of wet methods is necessary. Using a coprecipitation method, La_{1-x}Sr_xScO_{3-δ} (x = 0.01–0.2) oxides were obtained at final sintering temperature of 1600 °C with the resulting density 94–99 % [29]. Later, Kuzmin et al. studied the influence of the synthesis technique on the resulting density of La_{0.95}Sr_{0.05}ScO_{3-δ} ceramics [30]. The solid state reaction method resulted in poor sinterability and the relative density of about 70–75 % after 10 h of sintering at 1700 °C. The combustion method with nitrates as precursors resulted in 92–96 % relative density at the same temperature. When using oxides as precursors for the combustion method, a relative density of more than 98 % was achieved after 5 h of sintering at 1650 °C [30].

Another way to obtain dense ceramic is the use of sintering aids, which have been well studied and often applied for proton conductors based on cerates and zirconates [31–34]. Few data exist for LaScO₃ - based oxides. Thus, the influence of the addition of CuO, ZnO, Al₂O₃, NiO, Fe₂O₃, Co₃O₄ and MoO₃ on the sinterability, microstructure, and electrical properties of La_{0.9}Sr_{0.1}ScO_{3-α} ceramics was studied by Kuzmin et al. [35]. The relative density of La_{0.9}Sr_{0.1}ScO_{3-α} tubes without sintering aids was approximately 86 %. The introduction of 1.0 wt % ZnO, Al₂O₃, NiO or 0.5–1.0 wt % Co₃O₄ leads to a relative density of ceramics higher than 95 %. The introduction of 1 wt % Fe₂O₃ additive did not affect the sinterability of the La_{0.9}Sr_{0.1}ScO_{3-α} and 1 wt % CuO and MoO₃ inhibited electrolyte sintering. Among dense ceramic tubes, La_{0.9}Sr_{0.1}ScO_{3-α} with 0.5 wt % Co₃O₄ had the highest electrical conductivity. From the other side, for La_{1-x}Ba_xScO_{3-δ} it was observed that with an increase in the Ba content the relative density of the ceramics decreased from approximately 94 % for x = 0.025 to around 76 % for x = 0.1 [36]. In order to improve sinterability of the La_{1-x}Ba_xScO_{3-δ} oxides, Co₃O₄ was

applied as a sintering additive. However, an addition of only 0.5 wt % of Co₃O₄, despite the positive sintering effect, caused a noticeable violation of stoichiometry, with partial decomposition of the material, as well as a partial substitution of Sc with Co in La_{1-x}Ba_xScO_{3-δ}. Highly dense samples (98 %) were obtained only by high-temperature sintering at 1800 °C [36].

The basic compound LaScO₃, as well as the majority of LaScO₃ - based oxides, crystallize at room temperature in the perovskite structure with orthorhombic distortions, space group *Pnma*. Table 1 summarizes some data available in the literature. Only for the La_{0.6}Ba_{0.4}ScO₃ the cubic structure was reported [27], which is due to the larger size of the barium cation compared to lanthanum.

The main feature of SSPCs is the initial absence of protons in their structure. Protonic charge carriers appear at elevated temperatures due to the interaction between oxygen vacancies in the oxide structure and water vapor according to the

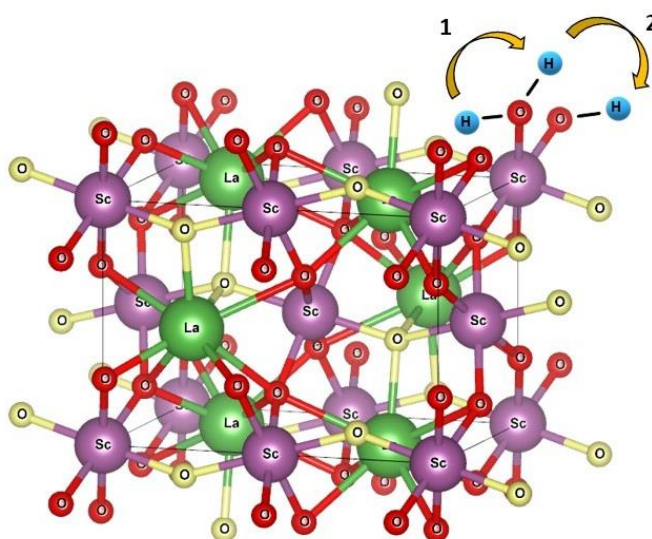


A proton is an elementary particle with a positive charge, which size is very small compared to the size of other ions in the oxide lattice. The interstitial proton is located close to oxygen and can be represented as an *OH* group occupying the oxygen site, i.e. *OH*. The main stages of proton transport are rotational diffusion of the proton defect and the proton transfer towards the neighboring oxygen ion, that is, only the proton diffuses, while the oxygen ions remain in their crystallographic positions (Figure 1). Rotational diffusion was shown to be a fast process with low activation energy [39]. This suggests that the rate-limiting stage of proton transport in perovskites is the transfer of a proton to a neighboring oxygen ion. Therefore, its activation energy depends on the distance between oxygen ions, and their electronic state. Due to orthorhombic distortions in LaScO₃, oxygen positions are not equivalent, and there are preferable positions for proton localization. In [26] by powder neutron diffraction the crystal structures of 20 mol. % Sr-doped LaScO₃ treated in H₂O were investigated. It was found that protons are associated with the O1 oxygen (4c) site in the La and Sr containing mirror plane and exist in the space consists of two tilting ScO₆ octahedra. The O1 – H bond distance was found to be 1.12(2) Å at 3 K. Later, the same conclusion about preferable proton sites was done by Farlenkov et al. on the La_{0.9}Sr_{0.09}ScO_{3-δ} oxide [37].

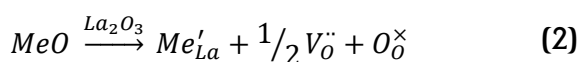
From the Reaction I it is obvious that for the appearance of protonic defects the existence of the oxygen vacancies is necessary. The most common way to

Table 1 – Crystal structure parameters for LaScO₃ - based oxides at room temperature.

Composition	<i>a</i> , Å	<i>b</i> , Å	<i>c</i> , Å	<i>V</i> , Å ³	Source
LaScO ₃	5.7913(6)	8.0943(8)	5.6793(5)	266.23(5)	[37]
La _{0.96} Sr _{0.04} ScO _{3-δ}	5.7886(3)	8.0996(7)	5.6808(4)	266.35(2)	[37]
La _{0.91} Sr _{0.09} ScO _{3-δ}	5.7843(7)	8.1048(2)	5.6879(4)	266.65(8)	[37]
La _{0.9} Sr _{0.1} ScO _{3-δ}	5.7918(9)	8.1005(3)	5.6799(5)	266.48(6)	[30]
La _{0.95} Sr _{0.05} ScO _{3-δ}	5.749	8.031	5.629	–	[28]
La _{0.9} Sr _{0.1} ScO _{3-δ}	5.830	8.133	5.715	–	[28]
La _{0.85} Sr _{0.15} ScO _{3-δ}	5.829	8.132	5.711	–	[28]
La _{0.8} Sr _{0.2} ScO _{3-δ}	5.734	8.100	5.722	–	[28]
La _{0.75} Sr _{0.25} ScO _{3-δ}	5.738	8.110	5.736	–	[28]
La _{0.7} Sr _{0.3} ScO _{3-δ}	5.736	8.092	5.721	–	[28]
La _{0.6} Ba _{0.4} ScO _{2.8}	4.0931(4)	–	–	–	[27]
La _{0.97} Ca _{0.03} ScO _{3-δ}	–	–	–	265.83	[38]
La _{0.95} Ca _{0.05} ScO _{3-δ}	–	–	–	266.12	[38]
La _{0.9} Ca _{0.1} ScO _{3-δ}	–	–	–	267.88	[38]
La _{0.95} Ba _{0.05} ScO _{3-δ}	5.780	8.110	5.697	267.1	[36]

**Figure 1** LaScO₃ crystal structure and the scheme of proton transport: 1) rotation diffusion; 2) proton transfer.

create oxygen vacancies is cation acceptor doping, e.g. doping with the element with lower oxidation state. In this case, oxygen vacancies are formed for keeping the electroneutrality of the crystal according to



The majority of the papers are devoted to LaScO₃ - based oxides acceptor doped into La sublattice. Here, three dopants are possible: Ca, Sr, Ba. Lesnichyova et al. reported that for calcium-doped oxides, only samples with 3 and 5 mol. % of Ca were found to be single phase, while for 10 mol. % of Ca contained calcium-enriched impurity phases (according to EDX analysis), despite the fact that this sample was single-phase according to XRD [38]. On the other hand, Fujii et al. [25] presented

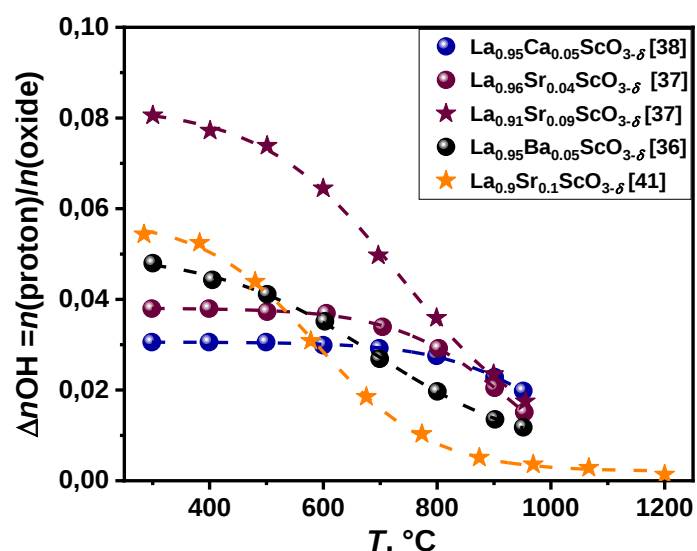
La_{1-x}Ca_xScO₃ (*x* = 0.05–0.2) as single-phase, but according only XRD data. For barium-doped oxides, Lesnichyova et al. prepared oxides with Ba content until 10 mol. %, all of them were reported to be single phase [36]. Kim et al. [27] reported La_{0.6}Ba_{0.4}ScO₃ to be single phase. Stroeve et al. studied doping with strontium in detail [29]. Oxides with a strontium content of up to 20 % were synthesized and all of them were found to be single phase [29]. Kato et al. [28] reported strontium solubility in LaScO₃ up to 30 mol. % of Sr.

Doping in Sc sublattice is less popular, since of the small radius of scandium. For example, Fujii et al. reported LaSc_{1-x}Mg_xO_{3-α} (*x* = 0–0.2) to be single phase [25]. However, usually doping in Sc-sublattice is carried out in conjunction with doping the lanthanum sublattice, most often with strontium. Stroeve et al. prepared La_{1-x}Sr_xSc_{1-y}Mg_yO_{3-α} (0.01 ≤ *x* = *y* ≤ 0.20) oxides, all of them were found to be single phase [40]. Kato et al. found that the presence of a small amount of aluminum in Sc-sublattice in La_{1-x}Sr_xSc_{1-y}Al_yO_{3-δ} (*y* = 0.01–0.05) led to the stabilization of the crystal structure suppressing phase transitions [28].

Because the formation of protonic defects according to Reaction 1 is accompanied by a significant weight increase, the concentration of protonic defects as a function of temperature and water partial pressure is usually measured by thermal gravimetric analysis (TGA). Additionally, from TGA data, thermodynamic parameters, such as enthalpy and entropy of hydration process can be estimated. Figure 2 compares results on proton concentration in LaScO₃ - based oxides available in literature. Generally, according to Equation 1, the value of maximum water uptake (saturation level) has to be

Table 2 – Hydration enthalpy ΔH_{hydr} and entropy ΔS_{hydr} values for proton conducting oxides.

Composition	ΔH_{hydr} , kJ · mol ⁻¹	ΔS_{hydr} , J · mol ⁻¹ · K ⁻¹	Experimental conditions		Source
			T , °C	$p_{\text{H}_2\text{O}}$, atm	
La _{0.96} Sr _{0.04} ScO _{3-δ}	-61 ± 5	-88 ± 5	300–950	0.24	[37]
La _{0.91} Sr _{0.09} ScO _{3-δ}	-97 ± 5	-112 ± 5			
La _{0.9} Sr _{0.1} ScO _{3-δ}	-105 ± 9	-116 ± 9	285–1200	0.019	[41]
La _{0.95} Ca _{0.04} ScO _{3-δ}	-132 ± 5	-126 ± 5	300–950	0.24	[38]
La _{0.95} Ba _{0.05} ScO _{3-δ}	-85 ± 6	-106 ± 6	300–950	0.24	[36]
BaZr _{0.9} Y _{0.1} O _{3-δ}	-79.4	-88.8	500–900	0.02	[43]
BaCe _{0.9} Y _{0.1} O _{3-δ}	-163.3	-167.9	600–850	0.02	[39]

**Figure 2** Temperature dependencies of proton concentration in LaScO₃ - based oxides.

equal to the acceptor doping concentration. One can see that for LaScO₃ - based oxides exact match between the saturation level n_{OH} and the acceptor concentration x is not observed. This phenomenon is often explained by the existence of a strong bond of the acceptor defects with oxygen vacancies, which do not participate in the hydration process [41]. In the case of LaScO₃ - based oxides, this phenomenon can be associated with oxygen vacancies not fully filled due to non-equality of O1 and O2 oxygen positions [26, 42].

Table 2 gives a comparison of the thermodynamic parameters of the hydration process for LaScO₃ - based oxides. The values are comparable with those for the best-known proton conducting oxides based on cerates and zirconates [39, 43].

3. Electrical properties

Generally, LaScO₃ - based oxides in an oxidizing atmosphere exhibit mixed oxygen-ionic, proton and hole conductivity, and in reducing conditions they exhibit pure ionic conductivity (mixed oxygen-ionic and proton). The contributions of different types of conductivity strongly depend on external conditions such as

temperature, oxygen and water vapor partial pressures, and the pure proton conductivity is usually observed at temperatures below 500 °C in reducing atmospheres.

Several works studied the influence of the level of doping and type of dopant on the electrical conductivity of the LaScO₃ - based oxides. Thus, Stroeve et al. studied the electrical conductivity of La_{1-x}Sr_xSc_{1-y}Mg_yO_{3-δ} ($x = y = 0.01$ – 0.2) in different atmospheres [40, 44]. Only a slight change in conductivity depending on the concentration of dopants was observed. As the temperature decreases, the maximum in the concentration dependencies of conductivity shifts to side of smaller additions of Sr and Mg. Lybye et al. compared the electrical conductivity data of La_{0.9}Sr_{0.1}ScO_{3-δ} and La_{0.9}Sr_{0.1}Sc_{0.9}Mg_{0.1}O_{3-δ} and concluded that in the case of LaScO₃ - based materials, Sr doping only in the A-sublattice is more effective than double doping of Sr and Mg in A and B-sublattice respectively [24]. The authors associate the decrease in the electrical conductivity of La_{0.9}Sr_{0.1}Sc_{0.9}Mg_{0.1}O_{3-δ} with the segregation of MgO at the grain boundaries, which they observed when studying samples using transmission electron microscopy. A decrease in bulk ionic conductivity and proton transfer numbers was also noted for La_{0.9}Sr_{0.1}Sc_{0.9}Mg_{0.1}O_{3-δ} compared to La_{0.9}Sr_{0.1}ScO_{3-δ} [45].

As follows from Reaction 2, the concentration of oxygen vacancies is proportional to the concentration of the dopant. Nevertheless, conductivity usually has a maximum at a certain dopant concentration and begins to decrease with its further increase since charged defects begin to interact with each other, leading to a decrease in their mobility [46]. Thus, for Sr-doped LaScO₃, despite the high Sr solubility in LaScO₃, the maximum of the electrical conductivity is observed for La_{0.9}Sr_{0.1}ScO_{3-δ} [45]. As dopants for the A-position, Ca, Sr, and Ba were studied [36, 38, 47]. Figure 3 compares electrical conductivity values for A-site doped LaScO₃ in air and reductive conditions. The temperature dependencies in reductive conditions demonstrate an inflection caused by the superposition of two types of ion transfer, i.e. oxygen ions

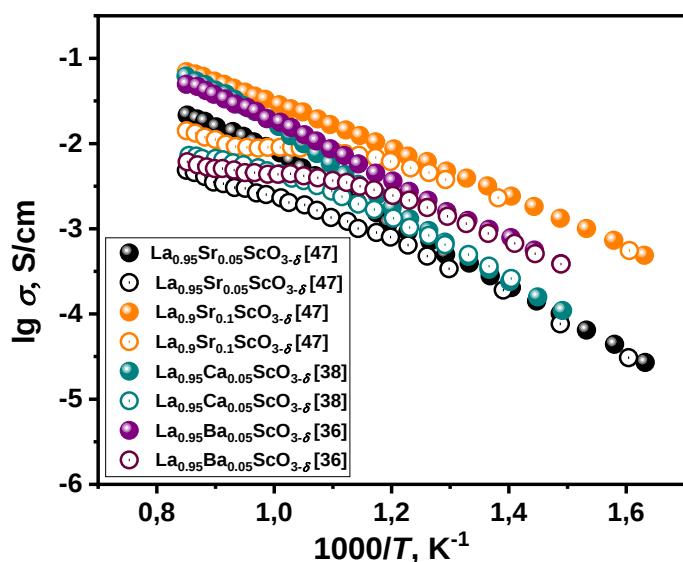


Figure 3 Temperature dependencies of the electrical conductivity for LaScO_3 -based oxides in air (filled symbols) and reductive (empty symbols) atmospheres.

at higher temperatures and protons at lower ones. Conductivity values in oxidizing and reducing atmospheres are close at temperatures below 500 °C, which indicates a low level of hole conductivity in air conditions, while at high temperatures they vary greatly due to the significant contribution of hole conductivity. Belyakov et al. using the pair distribution function and photoluminescence revealed the features of the crystal and electronic structures for $\text{La}_{0.95}\text{M}_{0.05}\text{ScO}_{3-\delta}$ ($\text{M} = \text{Ca}, \text{Sr}, \text{Ba}$) and studied the influence of the dopant on the hydration ability and electrical conductivity of the oxide [48]. They showed that the dopant-induced local distortions in the crystal structure and the electronic structure of the material influence the hydration process. Strontium was found to be the optimal dopant due to the combination of high proton stability and mobility. In summary, the best combination of doping level, electrical conductivity, phase stability and mechanical properties is observed for 10 mol. % Sr-doped LaScO_3 .

Since that for electrochemical application polycrystal materials are applied, it is important to know the contributions of bulk and grain boundaries to the total resistance of the ceramics. These data can be obtained by impedance spectroscopy measurements. It is well known that the bulk resistance is an intrinsic property of the material, determined by chemical composition and crystal structure. In contrast, grain boundary conductivity can differ in a wide range depending on different techniques of sample preparation, purity of the starting reagents, etc., resulting in different microstructure (grain size, purity of grain boundaries, porosity). Kuzmin et al. compared bulk and grain boundary conductivities of

5 mol. % Sr-doped LaScO_3 ceramics obtained by three different methods with different porosity and grain size [30]. It was found that bulk conductivities and their activation energy in the air atmosphere did not depend on the density of the samples. Activation energy of grain boundary and bulk conductivities were almost identical for the samples with 94 % and 98 % densities, while for the sample with 70 % density it was sufficiently higher. The authors conclude that for the samples with low porosity, there are no additional barriers for charge carriers on the grain boundaries compared to the charge transfer in the bulk, and the lower grain boundary conductivity is caused by fewer carriers crossing the grain boundaries. The bridge model on semi-coherent boundaries i.e. such boundaries, when only a part of atomic lattice planes of one grain continues in the lattice of another grain is proposed for explaining a low grain boundary conductivity. Such a boundary in a solid electrolyte accumulates complex defects: clusters of point defects, nanopores, and impurities. With increasing the porosity of the sample, the concentration of such defects increases and the semi-coherent boundary becomes incoherent with low conductivity and high activation energy, which is observed for the sample with 70 % density. Since the LaScO_3 -based oxides have a non-cubic lattice, it is impossible to reach high boundary coherence even for high-density samples, therefore, such materials will always exhibit higher grain boundary resistance compared to the bulk one. In order to get rid of low conducting boundaries, these materials should be used in the form of pseudo monocrystalline films, i.e. films with a grain size not less than its thickness.

4. Applications in the electrochemical devices

$\text{La}_{0.675}\text{Sr}_{0.325}\text{Sc}_{0.99}\text{Al}_{0.01}\text{O}_3$ was applied as an electrolyte membrane in an electrolyte-supported fuel cell in [49]. Using Pt, Ni-YSZ Ni-SDC as anodes, and Pt or $\text{La}_{0.8}\text{Sr}_{0.2}\text{MnO}_3$ as cathodes, the resulting power density was 47 $\text{mW} \cdot \text{cm}^{-2}$ when the cathode and anode were both platinum. At 1000 °C, the maximum power density was 158 $\text{mW} \cdot \text{cm}^{-2}$ with humidified hydrogen fuel using Ni-SDC and LSM as the anode and cathode, respectively. Further, the same authors manufactured and tested anode-supported fuel cell on the NiO-8YSZ substrate [50]. $(\text{La}_{0.675}\text{Sr}_{0.325})(\text{Sc}_{0.98}\text{Co}_{0.02})\text{O}_{3-\delta}$ thin film was deposited onto the substrate by pulsed laser deposition method, Pt was applied as a cathode. However, very low power densities were obtained: 21.6, 8.8, 3.5, and 1.9 $\text{mW} \cdot \text{cm}^{-2}$ at 780, 700, 650, and 600 °C, respectively. It was suggested that both the low electrical performances in the electrolyte and the unsuitable electrodes were responsible for this poor performances.

Plekhanov et al. made an attempt to modify $\text{La}_{0.9}\text{Sr}_{0.1}\text{ScO}_{3-\delta}$ electrolyte by transition metals and apply the obtained oxides as an electrolyte component in composite electrodes for $\text{La}_{0.9}\text{Sr}_{0.1}\text{ScO}_{3-\delta}$ [51]. It was shown that $\text{La}_{0.9}\text{Sr}_{0.1}\text{Sc}_{0.9}\text{Co}_{0.1}\text{O}_{3-\delta}$ has the highest value of conductivity among other compositions. A single fuel cell $\text{La}_{0.9}\text{Sr}_{0.1}\text{Sc}_{0.9}\text{Co}_{0.1}\text{O}_{3-\delta} - \text{LaFe}_{0.6}\text{Ni}_{0.4}\text{O}_3 \mid \text{La}_{0.9}\text{Sr}_{0.1}\text{ScO}_{3-\delta} \mid \text{La}_{0.9}\text{Sr}_{0.1}\text{Sc}_{0.9}\text{Co}_{0.1}\text{O}_{3-\delta} - \text{Ni}$ was tested and the maximum power density of the cell reached $35.5 \text{ mW} \cdot \text{cm}^{-2}$ at 800°C . The authors consider high electrolyte resistance to be the main obstacle for better performance. Nevertheless, the fuel cell with $\text{La}_{0.9}\text{Sr}_{0.1}\text{Sc}_{0.9}\text{Co}_{0.1}\text{O}_{3-\delta}$ in both electrodes has significantly better performance compared to the cell with $\text{La}_{0.9}\text{Sr}_{0.1}\text{ScO}_{3-\delta}$ component in the electrodes, which had a maximum power density of $0.14 \text{ mW} \cdot \text{cm}^{-2}$ at 800°C . Kuzmin et al. obtained close result of $30 \text{ mW} \cdot \text{cm}^{-2}$ for a single tubular fuel cell made on a supporting $\text{La}_{0.9}\text{Sr}_{0.1}\text{ScO}_{3-\delta}$ electrolyte with the same electrodes [35]. Finally, in recent work, Osinkin et al. tested an electrochemical cell based on $\text{La}_{0.9}\text{Sr}_{0.1}\text{ScO}_{3-\delta}$ electrolyte as a hybrid setup for electricity generation in the proton ceramic fuel cell mode, for hydrogen separation from the $\text{H}_2 + \text{Ar}$ mixture and the production of high-purity hydrogen from methane with simultaneous CO_2 utilization [52]. Symmetrical $\text{Sr}_{1.95}\text{Fe}_{1.4}\text{Ni}_{0.1}\text{Mo}_{0.5}\text{O}_{6-\delta} + \text{La}_{0.9}\text{Sr}_{0.1}\text{Sc}_{0.9}\text{Co}_{0.1}\text{O}_{3-\delta}$ composite electrodes were applied on the supporting $\text{La}_{0.9}\text{Sr}_{0.1}\text{ScO}_{3-\delta}$ electrolyte. In the fuel cell mode, the same values of the power density of about $33 \text{ mW} \cdot \text{cm}^{-2}$ were obtained, suggesting that regardless of the activity of the electrodes, the ohmic resistance of the supporting electrolyte primarily determines the power of such a cell. Another possible reason for not achieving high power density values is the presence of electronic (hole) conductivity in the $\text{La}_{0.9}\text{Sr}_{0.1}\text{ScO}_{3-\delta}$ supporting electrolyte on the side of the oxidizing atmosphere, leading to a decrease in the cell power due to the leakage current. In the mode of hydrogen separation through a proton-conducting membrane from an $\text{H}_2 + \text{Ar}$ mixture, a flow rate of hydrogen about of $500 \text{ cm}^3 \cdot \text{h}^{-1} \cdot \text{cm}^{-2}$ at a current density of $0.6 \text{ A} \cdot \text{cm}^{-2}$ was obtained at 800°C . During the hydrogen separation from methane and carbon dioxide mixture at a current density of $0.5 \text{ A} \cdot \text{cm}^{-2}$, the hydrogen flow rate was about $370 \text{ cm}^3 \cdot \text{h}^{-1} \cdot \text{cm}^{-2}$ at 800°C , which shows that these cells are promising for hydrogen production.

5. Conclusions

Solid state proton conductors are of great interest due to their possible application in the solid state electrochemical devices working in the medium-

temperature range ($500\text{--}700^\circ\text{C}$). Among them, LaScO_3 -based oxides are promising candidates, competing with well-known zirconates and cerates of alkaline-earth elements due to the combination of a sufficient level of proton conductivity with good chemical stability in the H_2O and CO_2 -containing atmospheres. The structural and functional properties of various LaScO_3 -based oxides are already well studied, and the most promising composition is found to be 10 mol. % oped LaScO_3 . Several attempts have been made to apply this electrolyte in electrochemical cells, and promising results have been obtained. However, there are still several issues that need to be resolved. It is necessary to develop technologies for obtaining dense thin films in order to decrease the ohmic resistance of the cells, with special attention to obtain large grains for decreasing the grain boundary resistance. Another obstacle is the presence of hole conductivity in the electrolyte at high temperatures, and therefore, a decrease in cell performance due to the leakage current. This can be overcome by decreasing the operating temperatures of the electrochemical devices up to $500\text{--}600^\circ\text{C}$, where the contribution of hole conductivity in the electrolyte is less pronounced. However, in this case, the problem of suitable electrodes efficiently operating at such temperatures arises.

Supplementary materials

No supplementary materials are available.

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Author contributions

Ekaterina Antonova: Conceptualization; Writing – Original draft; Writing – Review & Editing; Visualization.

Conflict of interest

The authors declare no conflict of interest.

Additional information



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