$LaGaO_3$-Based Solid Oxide Fuel Cell Electrolytes

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Solid oxide fuel cells (SOFCs) are efficient electrochemical devices that allow for the direct conversion of fuels (their chemical energy) into electricity. Although conventional SOFCs based on YSZ electrolytes are widely used from laboratory to commercial scales, the development of alternative ion-conducting electrolytes is of great importance for improving SOFC performance at reduced operation temperatures. The basic information has been studied on representative family of oxygen-conducting electrolytes, such as doped lanthanum gallates ($LaGaO_3$). Complex oxides based on $LaGaO_3$ offer a convenient basis for the design of oxygen-conducting electrolytes that can be employed in intermediate-temperature solid oxide fuel cells. A rational combination of appropriate dopants incorporated at various sublattices of $LaGaO_3$ allows superior transport properties to be achieved for co-doped derivatives ($La_{1-x}Sr_xGa_{1-y}Mg_yO_{3-\delta}$, LSGM).

SOFC solid oxide fuel cells LaGaO3 lanthanum gallate LSGM

oxygen-ion conductors solid electrolytes

1. Introduction

The long-term goal of a large body of relevant scientific research is to find a solution to the problem of providing industrial and domestic human needs with renewable and environmentally friendly energy [1][2]. The main fields of sustainable energy concern both the search for renewable energy sources [3][4][5] and methods for the production of ecological types of energy [6][7][8][9], which differ from traditional types based on hydrocarbon fuel [10][11][12]. The tasks relating to sustainable energy also include the development of technologies for the use of non-renewable energy sources: efficient waste-processing [13][14][15], the construction of nuclear mini-reactors [16], and the creation of energy devices based on the direct conversion of various types of energy into electrical and thermal energy [17][18][19]. A well-known device for directly converting the chemical energy of fuels into electrical energy is a fuel cell [19][20][21]. If the electrolyte in the fuel cell is a ceramic material that is permeable to oxygen ions, it is referred to as a solid oxide fuel cell (SOFC) [21][22][23][24][25].

The advantages of SOFCs are the absence of noble metals in their composition and the flexibility of fuel types [24][26][27], while the disadvantages include high operating temperatures, which lead to chemical interactions between the parts of the SOFCs [28][29] and fast degradation [30][31][32]. The high temperatures required to operate SOFCs with conventional electrolytes on the basis of yttria-stabilized zirconia (YSZ) lead to the formation of metastable phases, sealing, and thermal and chemical incompatibility with electrode materials [33][34][35].

One of the ways to solve the described problem is to decrease the operating temperature of SOFCs and develop fuel cells operating at medium- [36][37][38] and low-temperature ranges [39][40]. This has resulted in investigations into new classes of electrolytes [41][42][43][44] and the development of SOFCs enhanced with nanostructured materials [45][46]. The utilization of nanotechnologies, energy production and energy storage devices is extremely prospective due to their durability, sustainability, long lifetime, and low cost [47]. Among the alternative electrolytes used in low- and intermediate-temperature SOFCs, complex oxides with an ABO_3-type perovskite structure have attracted specific attention due to their high efficiency in energy conversion [48][49][50]. Sr, Mg-doped lanthanum gallate ($LaGaO_3$), possessing a high oxide ionic conductivity, which was established originally by Ishihara et al. in 1994 [51], was first used in SOFCs by Feng and Goodenough in 1996 [52].

Earlier, there was only one overview dedicated to Sr, Mg-doped $LaGaO_3$ oxides as electrolytes for intermediate-temperature solid oxide fuel cells: this was published by Morales et al. in 2016 [53]. The current studies is dedicated to recent progress in the design, characterization and application of electrolyte materials for SOFCs based on the doped $LaGaO_3$ complex oxides with a perovskite structure. The doped $LaGaO_3$ and $LaAlO_3$ phases constitute a family of oxygen-conducting electrolytes, while other La-based perovskites ($LaScO_3$, $LaInO_3$, $LaYO_3$, $LaYbO_3$) exhibit protonic conductivity as well [49].

2. Synthesis, Structure and Morphology

Historically, $La_{1-x}Sr_xGa_{1-y}Mg_yO_{3-\delta}$ (LSGM) oxides were the first well-studied doped materials in the $LaGaO_3$ system. In 1998, Huang, Tichy and Goodenough determined the existence of single-phase $La_{1-x}Sr_xGa_{1-y}Mg_yO_{3-0.5(x+y)}$ perovskites while studying a $LaO_{1.5}$-SrO-$GaO_{1.5}$-MgO quasi-quaternary diagram [54]. This was possible due to variations in both x and y contents in a composition range of 0.05–0.30 with a step of 0.05. Sr- and Mg- co-doped $LaGaO_3$ samples were prepared from La_2O_3, $SrCO_3$, Ga_2O_3, and MgO using solid-state reaction technology. The obtained powders were pressed into pellets and calcined at 1250 °C for 12 h. After remilling and repressing, the final pellets were finally sintered in air at 1470 °C for 24 h and quenched in a furnace at 500 °C.

Similar conventional techniques for synthesizing $La_{1-x}Sr_xGa_{1-y}Mg_yO_{3-\delta}$ were used in other studies [55][56]. $La_{0.9}Sr_{0.1}Ga_{0.8}Mg_{0.2}O_{3-\delta}$ samples were obtained from La_2O_3, $SrCO_3$, Ga_2O_3 and MgO sources, which were mixed and sintered in a platinum crucible at 1350 °C for 12 h [55]. The annealed powder was milled with zirconia balls and dried. Then, the powder was pressed into disks and sintered at 1350 °C in air, nitrogen or oxygen atmospheres for various times ranging from 20 min to 5 h. Moure et al. [56] obtained $La_{0.8}Sr_{0.2}Ga_{0.85}Mg_{0.15}O_{3-\delta}$ and $La_{0.8}Sr_{0.15}Ga_{0.85}Mg_{0.2}O_{3-\delta}$ samples from La_2O_3, $SrCO_3$, Ga_2O_3 and MgO, which were mechanochemically activated in a Pulverizette 6 Fritsch planetary mill with stainless steel balls. The mixtures were synthesized at 1300 °C for 16 h; then after milling for 2 h and sieving with a 100-μm sieve, the powders were pressed into pellets and finally sintered at 1550 °C to form the desired ceramic samples.

For the synthesis of $La_{0.9}Sr_{0.1}Ga_{1-x}Ni_xO_{3-\delta}$, Colomer and Kilner [57] grinded a mixture of La_2O_3, $SrCO_3$, Ga_2O_3 and NiO in an agate mortar with acetone medium and then calcined them at 1000 °C for 6 h. After sieving with a 65-μm sieve, milling for 1 h, drying and secondary sieving to 65 μm, the finishing powders were pressed into disks and sintered at 1450–1500 °C for 48 h in air. The researchers chose nickel as element for gallium substitution in $La_{0.9}Sr_{0.1}GaO_{3-\delta}$ owing to the proposal about achieving a hopping conductivity among the Ni-sites.

Al-substituted $La_{0.95}Sr_{0.05}Ga_{0.9}Mg_{0.1}O_{3-\delta}$ and $La_{0.9}Sr_{0.1}Ga_{0.8}Mg_{0.2}O_{3-\delta}$ derivatives were prepared using La_2O_3, Ga_2O_3, SrO, MgO and Al_2O_3 [58]. Mechanosynthesis was employed in a planetary mill (Retsch PM100, PM200) with tetragonal zirconia balls. The powders were pressed into disks that were sintered at 1300–1450 °C for 2–24 h.

As can be seen, the aforementioned methods (solid-state reaction synthesis and the mechanochemical route) that were conventionally used for the preparation of $La_{1-x}Sr_xGa_{1-y}Mg_yO_{3-\delta}$ and its derivatives have two considerable disadvantages. First, high sintering temperatures (above 1450–1500 °C) are required for full densification of the pressed pellets [51]. This can influence the production cost of the final electrolyte materials. Second, the appearance of $Sr_3La_4O_9$, $SrLaGa_3O_7$ and/or $SrLaGaO_4$ impurity phases in $La_{1-x}Sr_xGa_{1-y}Mg_yO_{3-\delta}$ samples was frequently observed. This was due to gallium evaporation [59], which resulted in the deterioration of the gallate material's ionic conductivity [51]. To solve the problems that arise during $La_{1-x}Sr_xGa_{1-y}Mg_yO_{3-\delta}$ preparation, techniques based on co-precipitation [60][61], organic-nitrate precursors combustion [55][62][63][64][65][66][67][68], self-propagating, high-temperature synthesis [69][70] and spray-pyrolysis [71] were developed.

For example, $La_{0.8}Sr_{0.2}Ga_{0.8}Mg_{0.2}O_{3-\delta}$ samples were prepared with carbonate co-precipitation from $La(NO_3)_3{\cdot}6H_2O$, $Sr(NO_3)_2$, $Ga(NO_3)_3{\cdot}xH_2O$ and $Mg(NO_3)_2{\cdot}6H_2O$ starting reagents [60]. The resulting aqueous solution containing La^{3+}, Sr^{2+}, Ga^{3+} and Mg^{2+} cations was gradually dropped into an aqueous $(NH_4)_2CO_3$ solution with heating at 70 °C. After 2 h of homogenization with continuous stirring, the formed sediments were washed, dried at 25 °C for 24 h in a N_2 atmosphere, and finally calcined in air at 900–1300 °C for 12 h.

Huang and Goodenough [63] have reported the use of wet synthesis techniques (the sol-gel technique and the Pechini method) for forming single-phase $La_{0.8}Sr_{0.2}Ga_{0.83}Mg_{0.17}O_{3-\delta}$ materials. Solutions of $La(CH_3COO)_3$, $Sr(CH_3COO)_2$ and $Mg(CH_3COO)_2$ acetates and $La(NO_3)_3$, $Sr(NO_3)_2$, $Ga(NO_3)_3$ and $Mg(NO_3)_2$ nitrates were used in these preparation methods. During synthesis with sol-gel technology, the required amounts of metal acetates and gallium nitrate solutions were mixed by stirring. An ammonia solution was then added, forming a white gel. This was aged at 25 °C for 72 h and heated at 150 °C for 8 h upon full water evaporation. The resulting product was fired at 300, 500 and 700 °C at varying times. Using the Pechini method, $La_{0.8}Sr_{0.2}Ga_{0.83}Mg_{0.17}O_{3-\delta}$ samples were prepared from a mixture of the necessary amounts of metal nitrate solutions at 25 °C: citric acid was then added. The citric acid was used to fulfil a mole ratio of citric acid/total cations around 1.5/1. After stirring the precursor solution, ethylene glycol was added in an equal amount to the citric acid. The obtained solution was heated at 150 °C for 12 h and resulted in a polymer-like solid material. This resin was slowly heated to 300 °C and, after several sintering stages, it was finally calcined at 1400 °C for 4 h [63]. The pressed $La_{0.85}Sr_{0.15}Ga_{0.8}Mg_{0.2}O_{3-\delta}$ samples were found to be single-phase after they were obtained via the Pechini method and annealed at 1400 °C for 6 h [64].

A $La_{0.8}Sr_{0.2}Ga_{0.85}Mg_{0.15}O_{3-\delta}$ sample was also obtained via the glycine-nitrate combustion method [65]. Ga, La_2O_3, MgO and $SrCO_3$ powders were dissolved in strong HNO_3 and mixed with water. Glycine was then added with a molar ratio of glycine/nitrate ions equal to 1:1. The glass beaker with the precursor glycine–nitrate solution was heated on a hot plate with spontaneous burning, which resulted in a white powder. Dense samples were formed at a temperature range of 1400–1550 °C for 6 h at each stage [65]. A similar method was used in [66] for the synthesis of $La_{0.9}Sr_{0.1}Ga_{0.8}Mg_{0.2}O_{3-\delta}$. The experimental procedure included the heating of the precursor glycine–nitrate solution at 550 °C upon combustion, initial calcination of voluminous oxide powders at 800 °C for 3 h, annealing the powders at 1000 °C and final annealing at 1300 °C for 2 h. It should be noted that the researchers of [66] could not achieve single-phase sample. Huang and Goodenough also concluded that a $La_{0.8}Sr_{0.2}Ga_{0.83}Mg_{0.17}O_{3-\delta}$ single-phase material cannot be formed via hydrothermal treatment synthesis [63].

In [69], Ishikawa et al., prepared $La_{0.9}Sr_{0.1}Ga_{0.8}Mg_{0.2}O_{3-\delta}$ and $La_{0.9}Sr_{0.1}Ga_{0.7}Mg_{0.3}O_{3-\delta}$ samples via self-propagating high-temperature synthesis from La_2O_3, $SrCO_3$, Ga_2O_3, Mg and $NaClO_4$. An initial powder mixture was supplied to a self-propagating synthesis reactor: it was then ignited with a disposable carbon foil in contact with the sample. The obtained powders were washed with water to remove NaCl. The samples were pressed into disks in vacuum and then sintered at a temperature range of 1000–1500 °C for 6 h in air. An alternative process for $La_{0.9}Sr_{0.1}Ga_{0.8}Mg_{0.2}O_{3-\delta}$ synthesis based on a preliminarily mechanically activated powder mixture was proposed by Ishikawa et al. [70]. The initial mixture was grinded in a planetary mill with stainless steel balls. The powder sample was pressed into a disk, which was placed in a self-propagating synthesis reactor: the aforementioned algorithm [69] was then used.

It is worth noting that the crystal structure of the obtained LSGM samples depends on the strontium and manganese dopant contents. Basic $LaGaO_3$ at room temperature has an orthorhombic structure [72] but varying the doping contents can change the crystal structure symmetry [63][73]. Generally, the substitution of La^{3+}-ions with Sr^{2+}-ions increases the tolerance factor t , while Ga-with-Mg substitution decreases it. Therefore, the t factor for $La_{1-x}Sr_xGa_{1-y}Mg_yO_{3-\delta}$ is nearly equal to that calculated for undoped $LaGaO_3$.

The t factor is equal to 1 for $La_{0.8}Sr_{0.2}Ga_{0.8}Mg_{0.2}O_{3-\delta}$, which exhibits an ideal *Pm-3m* cubic structure with a unit cell parameter of a = 3.9146(1) Å [73]. According to [73], the crystal structure of $La_{0.9}Sr_{0.1}Ga_{0.8}Mg_{0.2}O_{3-\delta}$ and $La_{0.9}Sr_{0.1}Ga_{0.9}Mg_{0.1}O_{3-\delta}$ samples was refined in a *I2/a* monoclinic space group.

The crystal structure of $LaGaO_3$ and $La_{0.9}Sr_{0.1}Ga_{0.8}Mg_{0.2}O_{3-\delta}$ samples was investigated via powder neutron diffraction at 25, 800 and 1000 °C in [74]. According to the Rietveld refinement analysis of the diffraction data collected at 25 °C, an orthorhombic structure was observed for both samples: fitting was provided in the *Pnma* space group for $LaGaO_3$ (unit cell parameters were equal to a = 5.4908(1), b = 7.7925(1) and c = 5.5227(1) Å) and in the *Imma* space group for $La_{0.9}Sr_{0.1}Ga_{0.8}Mg_{0.2}O_{3-\delta}$ (unit cell parameters were equal to a = 5.5179(1), b = 7.8200(1) and c = 5.5394(1) Å). The high temperature measurements [74] show that the $LaGaO_3$ sample possessed a rhombohedral structure in the *R-3c* space group (unit cell parameters were equal to a = 5.5899(1) Å and a = 5.5987(1) Å at 800 and 1000 °C, correspondingly), whereas $La_{0.9}Sr_{0.1}Ga_{0.8}Mg_{0.2}O_{3-\delta}$ exhibits a cubic structure in the *Pm3m* space group (unit cell parameters were equal to a = 3.9760(1) Å and a = 3.9866(1) Å at 800 and 1000 °C, correspondingly). Similar data at 25 °C (the *Imma* space group, a = 5.5056(9), b = 7.8241(7), c = 5.5387(5) Å) for a $La_{0.9}Sr_{0.1}Ga_{0.8}Mg_{0.2}O_{3-\delta}$ sample obtained via solid-state route and sintered at 1350 °C for 2 h was reported in [75].

Comparative analysis of the microstructural parameters for $La_{0.9}Sr_{0.1}Ga_{0.8}Mg_{0.2}O_{3-\delta}$ disks sintered at 1400 °C for 6 h obtained via the self-propagating high-temperature and solid-reaction synthesis techniques showed that the first sample was denser [69]. The relative densities of the samples were 98 and 92%, respectively, despite the fact that the sintering temperature for the first disk was 100 °C lower than that for the second one. These SEM images testify that mechanically activated self-propagating synthesis provided the high-grade powders with nano-size particles. The specific surface areas of the samples were 3.36 and 2.06 m^2 g^{-1}, respectively. Based on both studies, Ishikawa et al. [69][70] concluded that this proved the advantages of using self-propagating high-temperature synthesis (especially with mechanical activation of the starting mixture) in comparison with the solid-reaction method.

The evolution of a $La_{0.9}Sr_{0.1}Ga_{0.8}Mg_{0.2}O_{3-\delta}$ sample's density against temperature was provided in by Batista et al. [75]. Based on dilatometry experimental results, the researchers separated the process into three steps: an insignificant increase of relative density at 25–1000 °C; gradual densification at 1000–1300 °C; and, finally, a fast densification above 1300 °C. According to [76], a relative density of over 99% was achieved after calcination at 1450 °C for 6 h.

To sum up, which was devoted to the synthesis methods of Sr, Mg-doped $LaGaO_3$ oxides as electrolyte materials, the self-propagating high-temperature synthesis with mechanical activation of the starting mixtures can be identified as one of the most optimal techniques. The above-mentioned method can obtain the single-phase $La_{0.9}Sr_{0.1}Ga_{0.8}Mg_{0.2}O_{3-\delta}$ powders with high specific surface areas, a narrow distribution of nano-size particles, and high relative densities for the sintered ceramic samples.

3. Functional Properties

In 1994, Ishihara et al. [51] were the first to show that the La-substitution of $LaGaO_3$ with strontium and gallium with magnesium increased the electrical conductivity of doped materials owing to the formation of oxygen vacancies in $La_{1-x}Sr_xGa_{1-y}Mg_yO_{3-\delta}$ [77].

The measurements of Ishihara [51], Stevenson [78] and Goodenough [54] demonstrate that the $La_{1-x}Sr_xGa_{1-y}Mg_yO_{3-\delta}$ samples possess maximal electrical conductivity values at x = 0.15/0.2 and y = 0.2, as can be seen in **Table 1**. It should be also noted that conductivity of nominally similar materials can be varied over a wide range. This confirms that the microstructural parameters of ceramics, as well as the presence of insulating impurity phases, considerably affect the transport properties of gallates, encouraging the continuous search for their new synthesis and fabricating techniques.

Table 1. Total conductivities of $LaGaO_3$-based materials depending on their compositions, preparation methods and temperatures.

$LaGaO_3$	Solid-state route; 1500	950	0.02	[51]
$La_{0.9}Sr_{0.1}Ga_{0.9}Mg_{0.1}O_{3-\delta}$	Solid-state route; 1500	950	0.20	[51]
$La_{0.9}Sr_{0.1}Ga_{0.85}Mg_{0.15}O_{3-\delta}$	Solid-state route; 1500	950	0.27	[51]
$La_{0.9}Sr_{0.1}Ga_{0.8}Mg_{0.2}O_{3-\delta}$	Solid-state route; 1500	950	0.29	[51]
$La_{0.9}Sr_{0.1}Ga_{0.7}Mg_{0.3}O_{3-\delta}$	Solid-state route; 1500	950	0.28	[51]
$La_{0.9}Sr_{0.1}Ga_{0.6}Mg_{0.4}O_{3-\delta}$	Solid-state route; 1500	950	0.10	[51]
$La_{0.9}Sr_{0.1}Ga_{0.8}Mg_{0.2}O_{3-\delta}$	Glycine-combustion method; 1400	1000	0.26	[51]
$La_{0.85}Sr_{0.15}Ga_{0.8}Mg_{0.2}O_{3-\delta}$	Glycine-combustion method; 1400	1000	0.36	[51]
$La_{0.8}Sr_{0.2}Ga_{0.85}Mg_{0.15}O_{3-\delta}$	Glycine-combustion method; 1400	1000	0.31	[51]
$La_{0.8}Sr_{0.2}Ga_{0.8}Mg_{0.2}O_{3-\delta}$	Glycine-combustion method; 1400	1000	0.40	[51]
$La_{0.9}Sr_{0.1}Ga_{0.9}Mg_{0.1}O_{3-\delta}$	Solid-state route; 1470	800	0.116	[54]
$La_{0.9}Sr_{0.1}Ga_{0.85}Mg_{0.15}O_{3-\delta}$	Solid-state route; 1470	800	0.127	[54]
$La_{0.9}Sr_{0.1}Ga_{0.8}Mg_{0.2}O_{3-\delta}$	Solid-state route; 1470	800	0.132	[54]
$La_{0.9}Sr_{0.1}Ga_{0.7}Mg_{0.3}O_{3-\delta}$	Solid-state route; 1470	800	0.096	[54]
$La_{0.85}Sr_{0.15}Ga_{0.8}Mg_{0.2}O_{3-\delta}$	Solid-state route; 1470	800	0.150	[54]
$La_{0.8}Sr_{0.2}Ga_{0.85}Mg_{0.15}O_{3-\delta}$	Solid-state route; 1470	800	0.149	[54]
$La_{0.8}Sr_{0.2}Ga_{0.83}Mg_{0.17}O_{3-\delta}$	Solid-state route; 1470	800	0.17	[54]
$La_{0.8}Sr_{0.2}Ga_{0.8}Mg_{0.2}O_{3-\delta}$	Solid-state route; 1470	800	0.14	[54]
$La_{0.7}Sr_{0.3}Ga_{0.8}Mg_{0.2}O_{3-\delta}$	Solid-state route; 1470	800	0.109	[54]
$La_{0.9}Sr_{0.1}Ga_{0.8}Mg_{0.2}O_{3-\delta}$	Self-propagating high-temperature synthesis; 1500	800	0.11	[69]
$La_{0.9}Sr_{0.1}Ga_{0.8}Mg_{0.2}O_{3-\delta}$	Carbonate co-precipitation; 1400	800	0.045	[61]
$La_{0.9}Sr_{0.1}Ga_{0.9}Mg_{0.1}O_{3-\delta}$	Solid-state route; 1450	800	0.071	[73]
$La_{0.9}Sr_{0.1}Ga_{0.8}Mg_{0.2}O_{3-\delta}$	Solid-state route; 1450	800	0.1095	[73]
$La_{0.9}Sr_{0.1}Ga_{0.8}Mg_{0.2}O_{3-\delta}$	Glycine-combustion method; 1500	800	0.092	[79]

$La_{0.9}Sr_{0.1}Ga_{0.8}Mg_{0.2}O_{3-δ}$	Glycine-combustion method; 1400	800	0.0395	[80]
$La_{0.85}Sr_{0.15}Ga_{0.85}Mg_{0.15}O_{3-δ}$	Acrylamide polymerization technique; 1432	800	0.093	[81]
$La_{0.85}Sr_{0.15}Ga_{0.8}Mg_{0.2}O_{3-δ}$	Mechanochemical route; 1380	600	0.016	[56]
$La_{0.85}Sr_{0.15}Ga_{0.8}Mg_{0.2}O_{3-δ}$	Glycine-combustion method; 1300	800	0.053	[82]
$La_{0.85}Sr_{0.15}Ga_{0.8}Mg_{0.2}O_{3-δ}$	EDTA-combustion method; 1300	800	0.06	[82]
$La_{0.85}Sr_{0.15}Ga_{0.8}Mg_{0.2}O_{3-δ}$	Glycine-combustion method; 1400	800	0.096	[64]
$La_{0.85}Sr_{0.15}Ga_{0.8}Mg_{0.2}O_{3-δ}$	Pechini method; 1400	800	0.135	[83]
$La_{0.8}Sr_{0.2}Ga_{0.8}Mg_{0.2}O_{3-δ}$	Carbonate co-precipitation; 1300	600	0.014	[60]
$La_{0.8}Sr_{0.2}Ga_{0.8}Mg_{0.2}O_{3-δ}$	Glycine-combustion method; 1300	700	0.022	[68]
$La_{0.8}Sr_{0.2}Ga_{0.8}Mg_{0.2}O_{3-δ}$	Glycine-combustion method; 1400	700	0.085	[68]
$La_{0.8}Sr_{0.2}Ga_{0.8}Mg_{0.2}O_{3-δ}$	Spray pyrolysis; 1400	500	0.0029	[71]
$La_{0.8}Sr_{0.2}Ga_{0.8}Mg_{0.2}O_{3-δ}$	Solid-state route; 1450	800	0.126	[84]
$La_{0.8}Sr_{0.2}Ga_{0.8}Mg_{0.2}O_{3-δ}$	Solid-state route; 1400	800	0.035	[84]
$La_{0.8}Sr_{0.2}Ga_{0.8}Mg_{0.2}O_{3-δ}$	Hydrothermal urea hydrolysis precipitation; 1400	800	0.056	[84]
$La_{0.8}Sr_{0.2}Ga_{0.8}Mg_{0.2}O_{3-δ}$	Carbonate co-precipitation; 1400	800	0.137	[85]
$La_{0.8}Sr_{0.2}Ga_{0.8}Mg_{0.2}O_{3-δ}$	Solid-state route; 1250	727	0.019	[86]
$La_{0.8}Sr_{0.2}Ga_{0.8}Mg_{0.2}O_{3-δ}$	Sol-gel technique; 1300	450	2.9×10^{-4}	[87]
$La_{0.8}Sr_{0.2}Ga_{0.8}Mg_{0.2}O_{3-δ}$	Solid-state route; 1400	800	0.132	[88]
$La_{0.8}Sr_{0.2}Ga_{0.8}Mg_{0.2}O_{3-δ}$	Thin film deposited by vacuum cold spray; 200	750	0.043	[89]
$La_{0.8}Sr_{0.2}Ga_{0.8}Mg_{0.2}O_{3-δ}$	Step-wise current-limiting flash sintering process; 690	850	0.072	[90]

ter when factor for led to the -$LaGaO_3$ (nearly 20 mol.%, i.e., $x = y = 0.2$). The literature on the transport properties of $La_{1-x}Sr_xGa_{1-y}Mg_yO_{3-δ}$ ceramic samples is summarised in **Table 1**.

It was shown in [78] that the ion-transfer numbers were nearly equal to 1. For $La_{0.9}Sr_{0.1}Ga_{0.8}Mg_{0.2}O_{3-δ}$ and $La_{0.8}Sr_{0.2}Ga_{0.8}Mg_{0.2}O_{3-δ}$ ceramic samples, the oxygen-ion transference numbers were found to be equal 1 at 700–1000 °C [66], confirming the presence of electrolyte-type behaviour. Savioli and Watson [92] studied the defect structure of $LaGaO_3$ upon the use of various doping strategies using DFT calculations. They confirmed that Sr-, Ba-, and Mg-doping should result in the greatest improvements to the ionic conductivity of the $LaGaO_3$ parent phase, while the Ni^{2+}-, Co^{2+}-, Fe^{2+}-, and Zn^{2+}-doping is responsible for the generation of a mixed ionic-electronic conducting behaviour. Sr- and Mg- co-doped $LaGaO_3$ complex oxides are predominantly oxygen-ionic conductors, for which the electronic conductivity levels are 3–4 magnitudes lower compared to the oxygen-ionic conductivity levels [93].

According to [82], the dependence ln(σT) vs. 1/T had a break at 700 °C for $La_{0.85}Sr_{0.15}Ga_{0.8}Mg_{0.2}O_{3-\delta}$, which indicates that the activation energy value of oxygen-ion conductivity at a low-temperature range was higher than that at a high-temperature range.

A linear correlation between hardness and total ionic conductivity was revealed in [83] for $La_{0.9}Sr_{0.1}Ga_{0.8}Mg_{0.2}O_{3-\delta}$ and $La_{0.85}Sr_{0.15}Ga_{0.8}Mg_{0.2}O_{3-\delta}$ samples. It was shown that the electrical and mechanical properties of $La_{1-x}Sr_xGa_{1-y}Mg_yO_{3-\delta}$ are strongly defined by microstructural peculiarities and the presence of low-conductive $LaSrGaO_4$ and $LaSrGa_3O_7$ impurity phases [80]. The $LaSrGaO_4$ phase exhibits a tetragonal structure K_2NiF_4-type and crystalizes in the *I4/mmm* space group; its conductivity is found to be around $2{\cdot}10^{-7}$ S cm^{-1} at 900 °C [94]. The $LaSrGa_3O_7$ phase belongs to a melilitestructure described in the *P421m* space group; its ionic conductivity level is around $2{\cdot}10^{-6}$ S cm^{-1} at 800 °C [95]. The maximum values of ionic conductivity and hardness were achieved for single-phase $La_{0.9}Sr_{0.1}Ga_{0.8}Mg_{0.2}O_{3-\delta}$ (LSGM1020) and $La_{0.85}Sr_{0.15}Ga_{0.8}Mg_{0.2}O_{3-\delta}$ (LSGM1520) samples with a high relative density. With a significant amount of impurity phases at the grain boundaries, the samples exhibited a gradual decrease in hardness and the grain boundary conductivity, which resulted in a decreasing total conductivity.

The thermal expansion of $La_{1-x}Sr_xGa_{1-y}Mg_yO_{3-\delta}$ was studied by Baskaran et al. [96]. The TEC values measured for the $La_{0.9}Sr_{0.1}Ga_{0.8}Mg_{0.2}O_{3-\delta}$ sample were equal to 10×10^{-6} K^{-1} over a low-temperature range and 13.5–14.0 × 10^{-6} K^{-1} above 600 °C. Lee et al. [62] reported about an average TEC of 12.1×10^{-6} K^{-1} for $La_{0.8}Sr_{0.2}Ga_{0.8}Mg_{0.2}O_{3-\delta}$ at a temperature range of 25–1000 °C, which is close to 12.3×10^{-6} K^{-1} for a $La_{0.65}Sr_{0.3}MnO_{3-\delta}$ electrode at the same temperatures [97].

The expansion behaviour for $La_{1-x}Sr_xGa_{1-y}Mg_yO_{3-\delta}$ is correlated with its crystal structure in the observed temperature range. Therefore, the presence of a phase transition from an orthorhombic phase to a cubic one for $La_{0.9}Sr_{0.1}Ga_{0.8}Mg_{0.2}O_{3-\delta}$ [74] and the existence of an ideal perovskite cubic structure for $La_{0.8}Sr_{0.2}Ga_{0.8}Mg_{0.2}O_{3-\delta}$ [73] are responsible for the aforementioned variations in their thermal expansion behaviour.

Datta et al. [98] observed that the temperature of phase transition from an orthorhombic to a rhombohedral structure for $La_{1-x}Sr_xGa_{1-y}Mg_yO_{3-\delta}$ increased as Mg content increased at a fixed Sr content and decreased with increasing Sr content at a fixed Mg content. The effect of Sr and Mg co-doping on TEC values was explained for $La_{1-x}Sr_xGa_{1-y}Mg_yO_{3-\delta}$ in terms of the amount of generated oxygen vacancies. It was concluded that TEC values increased as oxygen vacancies increase, regardless of the dopant type. This was the result of the binding energy weakening as a result of oxygen vacancy formation.

Shkerin et al. [99] analysed the structure and phase transitions of $La_{0.88}Sr_{0.12}Ga_{0.82}Mg_{0.18}O_{3-\delta}$ using dilatometry, XRD and Raman spectroscopy. According to the obtained data, $La_{0.88}Sr_{0.12}Ga_{0.82}Mg_{0.18}O_{3-\delta}$ exhibited two phase transitions of the second order at 502 and 607 °C. The first transition was attributed to a phase transition from an orthorhombic phase to a cubic one, while the second phase transition was attributed to the ordering of the oxygen vacancies.

Wu et al. [100] studied transport properties of $La_{0.85}Sr_{0.15}Ga_{0.8}Mg_{0.2}O_{3-\delta}$ upon the partial or full Sr-substitution with calcium or barium. Their analyses have shown that both types of substitution result in a decrease in ionic conductivity by 20–30%. However, at the same time, the Ca-substituted ceramic materials showed higher conductivities compared to the Ba-substituted analogues. This confirms that strontium is an ideal dopant (from the steric and energetic viewpoints) to be introduced into the La-sublattice of $LaGaO_3$-based phases.

The chemical compatibility of $La_{1-x}Sr_xGa_{1-y}Mg_yO_{3-\delta}$ was investigated with oxide materials used in SOFCs, cathodes [101][102][103][104][105][106][107][108][109][110][111][112] and anodes [113][114][115][116][117][118][119][120][121][122][123][124][125][126][127], and it was presented in the corresponding research[28][53][113].

Chemical interactions between a $La_{0.9}Sr_{0.1}Ga_{0.8}Mg_{0.2}O_{3-\delta}$ electrolyte and cathode materials such as $La_{0.65}Sr_{0.3}MnO_{3-\delta}$, $La_{0.7}Sr_{0.3}CoO_{3-\delta}$, $La_{0.65}Sr_{0.3}FeO_{3-\delta}$, $La_{0.65}Sr_{0.3}NiO_{3-\delta}$ and $La_{0.6}Sr_{0.4}Co_{0.2}Fe_{0.8}O_{3-\delta}$ are demonstrated in [101]. The LSGM/cathode powders were mixed at a weight ratio of 1:1, pressed into disks and annealed at 1300 °C for 3 h in air. The XRD data revealed that impurity phases were not formed in the LSGM mixed with $La_{0.65}Sr_{0.3}MnO_{3-\delta}$, $La_{0.7}Sr_{0.3}CoO_{3-\delta}$, and $La_{0.65}Sr_{0.3}FeO_{3-\delta}$, but appear in the calcined mixtures with $La_{0.65}Sr_{0.3}NiO_{3-\delta}$ and $La_{0.6}Sr_{0.4}Co_{0.2}Fe_{0.8}O_{3-\delta}$. The absence of reactivity between $La_{0.8}Sr_{0.2}Ga_{0.8}Mg_{0.2}O_{3-\delta}$ and $La_{0.8}Sr_{0.2}MnO_{3-\delta}$ was also confirmed during calcination at 800 °C [102].

Sydyknazar et al. [103] showed that $La_{0.83}Sr_{0.17}Ga_{0.8}Mg_{0.2}O_{3-\delta}$ exhibited good chemical compatibility with a novel cathode material, $Sr_{0.9}Ba_{0.1}Co_{0.95}Ru_{0.05}O_{3-\delta}$, after joint calcination at 1100 °C for 12 h. According to the literature, $La_{0.9}Sr_{0.1}Ga_{0.8}Mg_{0.2}O_{3-\delta}$ does not react with the following cathodes: $La_{0.4}Sr_{0.6}Co_{0.9}Sb_{0.1}O_{3-\delta}$ after heat treatment at 1150 °C for 6 h [104], $SrCo_{0.8}Fe_{0.1}Nb_{0.1}O_{3-\delta}$ at 950 °C for 10 h [105], $BaCo_{0.7}Fe_{0.2}Ta_{0.1}O_{3-\delta}$ at 950 °C for 10 h [106] and $Sr_2Ti_{0.8}Co_{0.2}FeO_{6-\delta}$ after at 950 °C for 10 h [107]. According to Tarancón et al. [108], $La_{0.8}Sr_{0.2}Ga_{0.8}Mg_{0.2}O_{3-\delta}$ interacted with a $GdBaCo_2O_{5+\delta}$ cathode at temperatures above 900 °C, forming $BaLaGa_3O_4$ and $BaLaGa_3O_7$ secondary phases.

An analysis of works devoted to Ruddlesden–Popper phases demonstrates that $La_{0.9}Sr_{0.1}Ga_{0.8}Mg_{0.2}O_{3-\delta}$ and $Pr_{2-x}La_xNi_{0.85}Cu_{0.1}Al_{0.05}O_{4+\delta}$ (x = 0, 0.2, 0.5, 1.0) have no interactions at 1000 °C for 5 h [109], but $La_{0.95}Sr_{0.05}Ga_{0.9}Mg_{0.1}O_{3-\delta}$ reacted with $Nd_2NiO_{4+\delta}$ after annealing at 1000 °C for 5 h [110]. Equally, $La_{0.85}Sr_{0.15}Ga_{0.85}Mg_{0.15}O_{3-\delta}$ reacted with $Pr_{2-x}Ca_xNiO_{4+\delta}$ after annealing at 900 °C for 10 h (x = 0, 0.5) [111] and at 1200 °C for 1 h (x = 0, 0.3) [112].

Zhang et al. [114] showed that a $La_{0.9}Sr_{0.1}Ga_{0.8}Mg_{0.2}O_{3-\delta}$ electrolyte reacted with the nickel component in a Ni-SDC anode. The chemical interaction between LSGM and the composite was due to the interface diffusion of nickel from the anode to the LSGM electrolyte; this led to the formation of La-based poor-conductive secondary phases, which block oxygen-ion transport. The unit cell design with a buffer layer of SDC was suggested as an effective way of avoiding the problem of interface diffusion [115]. However, chemical reactivity was observed between $La_{1-x}Sr_xGa_{1-y}Mg_yO_{3-\delta}$ and buffer layers of $Gd_{0.1}Ce_{0.9}O_{1.95}$, scandia-doped zirconia [116] and $Gd_{0.8}Ce_{0.2}O_{1.9}$ [117].

An alternate solution to the problem of nickel interface diffusion from a Ni-based anode is to find novel anode materials. A study of the chemical compatibility between $La_{0.9}Sr_{0.1}Ga_{0.8}Mg_{0.2}O_{3-\delta}$ and Fe_2O_3, Co_2O_3, NiO as anode materials is provided in [118]. Powder mixtures of LSGM with metal oxides at a weight ratio of 1:1 were mixed in ethanol, pressed into pellets and annealed at 1150, 1250 and 1350 °C for 2 h. The obtained XRD data showed that the LSGM reacted with NiO and Co_2O_3 at 1150 °C, while a detectable reaction with Fe_2O_3 occurred only after calcination at 1350 °C.

Du and Sammes [119] reported good chemical compatibility between $La_{0.8}Sr_{0.2}Ga_{0.8}Mg_{0.2}O_{3-\delta}$ and an alternative $La_{0.75}Sr_{0.25}Cr_{0.5}Mn_{0.5}O_3$ anode at a temperature range of 1100–1500 °C. However, the researchers note that a low-conductivity phase formed if the annealing time was more than 6 h or the annealing temperature was greater than 1500 °C.

Good chemical compatibility between LSGM and anodes with a double perovskite structure was shown for: $La_{0.9}Sr_{0.1}Ga_{0.8}Mg_{0.2}O_{3-\delta}$ and $Sr_2TiMoO_{6-\delta}$ after calcining the samples at 1000 °C for 10 h in an atmosphere of 5% H_2/Ar [120], $La_{0.8}Sr_{0.2}Ga_{0.8}Mg_{0.2}O_{3-\delta}$ and $Sr_2Fe_{1.5}Mo_{0.5}O_{6-\delta}$ after heat treatment at 1200 °C for 24 h in air [121], $La_{0.88}Sr_{0.12}Ga_{0.82}Mg_{0.18}O_{3-\delta}$ with $Sr_2NiMoO_{6-\delta}$ at 1000 °C for 20 h [122][123] and $Sr_2Ni_{0.75}Mg_{0.25}MoO_{6-\delta}$ at 1100 °C for 20 h [124] and at 1250 °C for 2 h [123]. The formation of secondary phases between LSGM and double perovskite anodes was observed for $La_{0.9}Sr_{0.1}Ga_{0.8}Mg_{0.2}O_{3-\delta}$ and $Sr_2MgMoO_{6-\delta}$ after calcining at 1100 °C [125], for $La_{0.88}Sr_{0.12}Ga_{0.82}Mg_{0.18}O_{3-\delta}$ and Sr_2ZnMoO_6 at 1000 °C for 20 h [126] and for $La_{0.8}Sr_{0.2}Ga_{0.8}Mg_{0.2}O_{3-\delta}$ at 1300 °C for 10 h with $Sr_2Ni_{0.7}Mg_{0.3}MoO_{6-\delta}$ [127] and, after heat treatment at 1200 °C for 24 h, with $Sr_2CoMoO_{6-\delta}$ [121], $Sr_2NiMoO_{6-\delta}$ [121] and $Sr_2MgMoO_{6-\delta}$ [128].

According to Takano et al. [125], $La_{0.9}Sr_{0.1}Ga_{0.8}Mg_{0.2}O_{3-\delta}$ did not react with $Ce_{0.8}La_{0.2}O_{1.8}$ after annealing at 1300 °C for 1 h; therefore, it was concluded that $La_{0.9}Sr_{0.1}Ga_{0.8}Mg_{0.2}O_{3-\delta}$ and $Ce_{0.8}La_{0.2}O_{2-\delta}$ might be recommended as SOFC electrolyte and buffer materials, respectively, with $Sr_2MgMoO_{6-\delta}$ used as the anode material. However, a comprehensive investigation of the chemical compatibility between various compositions of $La_{1-x}Sr_xGa_{1-y}Mg_yO_{3-\delta}$ and lanthanum-doped CeO_2, provided in [129], showed that only a $La_{0.9}Sr_{0.1}Ga_{0.8}Mg_{0.2}O_{3-\delta}/Ce_{0.6}La_{0.4}O_{2-\delta}$ mixture did not result in additional phases after being annealed twice at 1350 °C for 2 h at each stage.

4. Applications in SOFCs

The problem of reactivity between the LSGM and SOFC electrode materials during sintering can be solved by reducing sintering temperatures or/and using the SDC buffer layer as a barrier, eliminating lanthanum- and nickel-cation diffusion. Several unit cell designs have been proposed in the literature. **Table 2** presents a summary of electrochemical performances for different types of hydrogen-fuelled SOFCs with LSGM-based electrolytes. These data testify that enhanced power densities were achieved for electrolyte-supported SOFCs when the LSGM electrolyte thickness was in a range of 100–300 μm. Buffer layers of doped ceria were used between the electrolyte and anode: $Ce_{0.8}Sm_{0.2}O_{2-\delta}$ [104][105][109][115][120][127], $Ce_{0.8}Gd_{0.2}O_{2-\delta}$ [130] and $Ce_{0.6}La_{0.4}O_{2-\delta}$ [131][132].

Table 2. The performances of SOFCs with $La_{1-x}Sr_xGa_{1-y}Mg_yO_{3-\delta}$ electrolytes.

Ni-$Ce_{0.8}Sm_{0.2}O_{2-\delta}$	$La_{0.8}Sr_{0.2}Ga_{0.83}Mg_{0.17}O_{3-\delta}$ (265)	$La_{0.6}Sr_{0.4}O_{3-\delta}$	800	290	[52]
Ni-$La_{0.8}Sr_{0.2}Ga_{0.83}Mg_{0.17}O_{2.815}$	$La_{0.8}Sr_{0.2}Ga_{0.83}Mg_{0.17}O_{3-\delta}$ (395)	$La_{0.6}Sr_{0.4}O_{3-\delta}$	800	363	[52]
Ni-$Ce_{0.8}Sm_{0.2}O_{2-\delta}$	$Ce_{0.8}Sm_{0.2}O_{2-\delta}/La_{0.9}Sr_{0.1}Ga_{0.8}Mg_{0.2}O_{3-\delta}$ (300)	$La_{0.4}Sr_{0.6}Co_{0.9}Sb_{0.1}O_{3-\delta}$-$Ce_{0.8}Sm_{0.2}O_{2-\delta}$	700	432	[104]
Ni-$Ce_{0.8}Sm_{0.2}O_{2-\delta}$	$Ce_{0.8}Sm_{0.2}O_{2-\delta}/La_{0.9}Sr_{0.1}Ga_{0.8}Mg_{0.2}O_{3-\delta}$ (100)	$SrCo_{0.8}Fe_{0.1}Nb_{0.1}O_{3-\delta}$	800	756	[105]
Ni-$Ce_{0.8}Sm_{0.2}O_{2-\delta}$	$Ce_{0.8}Sm_{0.2}O_{2-\delta}/La_{0.9}Sr_{0.1}Ga_{0.8}Mg_{0.2}O_{3-\delta}$ (100)	$SrCo_{0.8}Fe_{0.1}Nb_{0.1}O_{3-\delta}$–$Ce_{0.9}Gd_{0.1}O_{2-\delta}$	800	829	[105]
Ni-$Ce_{0.8}Sm_{0.2}O_{2-\delta}$	$La_{0.9}Sr_{0.1}Ga_{0.8}Mg_{0.2}O_{3-\delta}$ (300)	$BaCo_{0.7}Fe_{0.2}Ta_{0.1}O_{3-\delta}$	800	460	[106]
Ni-$Ce_{0.8}Sm_{0.2}O_{2-\delta}$	$Ce_{0.8}Sm_{0.2}O_{2-\delta}/La_{0.9}Sr_{0.1}Ga_{0.8}Mg_{0.2}O_{3-\delta}$ (300)	$Pr_2Ni_{0.85}Cu_{0.1}Al_{0.05}O_{4+\delta}$	700	392	[109]
Ni-$Ce_{0.8}Sm_{0.2}O_{2-\delta}$	$La_{0.8}Sr_{0.2}Ga_{0.83}Mg_{0.17}O_{3-\delta}$ (500)	$La_{0.6}Sr_{0.4}O_{3-\delta}$	800	270	[115] [133]
Ni-$Ce_{0.8}Sm_{0.2}O_{2-\delta}$	$Ce_{0.8}Sm_{0.2}O_{2-\delta}/La_{0.8}Sr_{0.2}Ga_{0.83}Mg_{0.17}O_{3-\delta}$ (500)	$La_{0.6}Sr_{0.4}O_{3-\delta}$	800	550	[115] [133]
Ni-$Ce_{0.8}Sm_{0.2}O_{2-\delta}$	$La_{0.87}Sr_{0.13}Ga_{0.85}Mg_{0.15}O_{3-\delta}$ (3.8)	$La_{0.87}Sr_{0.13}Ga_{0.85}Mg_{0.15}O_{3-\delta}$-$La_{0.6}Sr_{0.4}Fe_{0.8}Co_{0.2}O_{3-\delta}$	750	1420	[134]
Ni-$Ce_{0.8}Y_{0.2}O_{2-\delta}$	$La_{0.9}Sr_{0.1}Ga_{0.8}Mg_{0.2}O_{3-\delta}$ (45)	$La_{0.6}Sr_{0.4}O_{3-\delta}$	700	500	[135]
Ni-$Ce_{0.6}La_{0.4}O_{2-\delta}$	$La_{0.8}Sr_{0.2}Ga_{0.8}Mg_{0.2}O_{3-\delta}$ (30)	$La_{0.8}Sr_{0.2}Fe_{0.8}Co_{0.2}O_{3-\delta}$	700	780	[136]
Ni-$Ce_{0.6}La_{0.4}O_{2-\delta}$	$Ce_{0.6}La_{0.4}O_{2-\delta}/La_{0.8}Sr_{0.2}Ga_{0.83}Mg_{0.17}O_{3-\delta}$ (500)	$SrCo_{0.8}Fe_{0.2}O_{3-\delta}$	800	900	[137]
Ni-$Ce_{0.9}Gd_{0.1}O_{2-\delta}$	$Ce_{0.55}La_{0.45}O_{2-\delta}/La_{0.9}Sr_{0.1}Ga_{0.8}Mg_{0.2}O_{3-\delta}$ (75)	$La_{0.9}Sr_{0.1}O_{3-\delta}$-$Ce_{0.55}La_{0.45}O_{2-\delta}$	800	1100	[138]
Ni-$Ce_{0.9}Gd_{0.1}O_{2-\delta}$	$Ce_{0.55}La_{0.45}O_{2-\delta}/La_{0.9}Sr_{0.1}Ga_{0.8}Mg_{0.2}O_{3-\delta}$ (50)	$La_{0.6}Sr_{0.4}O_{3-\delta}$	800	1565	[139]
Ni-$Ce_{0.9}Gd_{0.1}O_{2-\delta}$	$Ce_{0.55}La_{0.45}O_{2-\delta}/La_{0.9}Sr_{0.1}Ga_{0.8}Mg_{0.2}O_{3-\delta}$ (50)/$Ce_{0.55}La_{0.45}O_{2-\delta}$	$La_{0.6}Sr_{0.4}O_{3-\delta}$	800	871	[139]
Ni-$Ce_{0.8}Gd_{0.2}O_{2-\delta}$	$Ce_{0.8}Gd_{0.2}O_{2-\delta}/La_{0.9}Sr_{0.1}Ga_{0.8}Mg_{0.2}O_{3-\delta}$ (75)	$Ba_{0.5}Sr_{0.5}Co_{0.8}Fe_{0.2}O_{3-\delta}$	700	760	[140]

Ni-Fe	$Ce_{0.8}Sm_{0.2}O_{2-\delta}/La_{0.9}Sr_{0.1}Ga_{0.8}Mg_{0.2}O_{3-\delta}$ (6)	$Sm_{0.5}Sr_{0.5}O_{3-\delta}$	700	1790	[141]
Ni-$Ce_{0.6}La_{0.4}O_{2-\delta}$	$Ce_{0.6}La_{0.4}O_{2-\delta}/La_{0.9}Sr_{0.1}Ga_{0.8}Mg_{0.2}O_{3-\delta}$ (9)/$Ce_{0.6}La_{0.4}O_{1.8}$	$La_{0.9}Sr_{0.1}Ga_{0.8}Mg_{0.2}O_{3-\delta}$-$La_{0.6}Sr_{0.4}Fe_{0.8}Co_{0.2}O_{3-\delta}$	700	910	[142]
Ni-$Ce_{0.8}Sm_{0.2}O_{2-\delta}$	$Ce_{0.6}La_{0.4}O_{2-\delta}/La_{0.9}Sr_{0.1}Ga_{0.8}Mg_{0.2}O_{3-\delta}$ (11)/$Ce_{0.6}La_{0.4}O_{1.8}$	$La_{0.9}Sr_{0.1}Ga_{0.8}Mg_{0.2}O_{3-\delta}$-$La_{0.6}Sr_{0.4}Fe_{0.8}Co_{0.2}O_{3-\delta}$	800	1230	[143]
Ni-$Ce_{0.8}Gd_{0.2}O_{2-\delta}$	$Ce_{0.8}Gd_{0.2}O_{2-\delta}/(La_{0.9}Sr_{0.1})_{0.97}Ga_{0.9}Mg_{0.1}O_{3-\delta}$ (120)	$La_{0.6}Sr_{0.4}Fe_{0.8}Co_{0.2}O_{3-\delta}$	800	540	[130]
Ni-$Ce_{0.8}Sm_{0.2}O_{2-\delta}$	$La_{0.9}Sr_{0.1}Ga_{0.8}Mg_{0.2}O_{3-\delta}$ (3.4)	$La_{0.9}Sr_{0.1}Ga_{0.8}Mg_{0.2}O_{3-\delta}$-$La_{0.6}Sr_{0.4}Fe_{0.8}Co_{0.2}O_{3-\delta}$	750	736	[144]
Ni-$Ce_{0.8}Gd_{0.2}O_{2-\delta}$	$La_{0.8}Sr_{0.2}Ga_{0.8}Mg_{0.2}O_{3-\delta}$ (50)	$La_{0.6}Sr_{0.4}Fe_{0.8}Co_{0.2}O_{3-\delta}$	700	831	[145]
Ni-Fe	$Ce_{0.6}La_{0.4}O_{2-\delta}/La_{0.9}Sr_{0.1}Ga_{0.8}Mg_{0.2}O_{3-\delta}$ (200)	$Sm_{0.5}Sr_{0.5}O_{3-\delta}$	800	1350	[131]
Pd-$Sr_2TiMoO_{6-\delta}$	$Ce_{0.8}Sm_{0.2}O_{2-\delta}/La_{0.9}Sr_{0.1}Ga_{0.8}Mg_{0.2}O_{3-\delta}$ (300)	$NdBaCo_{0.67}Fe_{0.67}Cu_{0.67}O_{5+\delta}$	850	1009	[120]
$Sr_2NiMoO_{6-\delta}$	$La_{0.88}Sr_{0.12}Ga_{0.82}Mg_{0.18}O_{3-\delta}$ (700)/$Ce_{0.8}Sm_{0.2}O_{2-\delta}$	$La_{0.7}Sr_{0.3}Fe_{0.9}Co_{0.1}O_{3-\delta}$	800	61	[123]
$Sr_2NiMoO_{6-\delta}$	$La_{0.9}Sr_{0.1}Ga_{0.8}Mg_{0.2}O_{3-\delta}$ (300)	$Ba_{0.5}Sr_{0.5}Co_{0.8}Fe_{0.2}O_{3-\delta}$	800	595	[146]
$Sr_2MgMoO_{6-\delta}$	$Ce_{0.8}Sm_{0.2}O_{2-\delta}/La_{0.8}Sr_{0.2}Ga_{0.8}Mg_{0.2}O_{3-\delta}$ (700)	$SmBaCo_2O_{5+\delta}$	800	39	[127]
$Sr_2MgMoO_{6-\delta}$	$Ce_{0.8}Gd_{0.2}O_{2-\delta}/La_{0.8}Sr_{0.2}Ga_{0.8}Mg_{0.2}O_{3-\delta}$ (600)	$La_{0.6}Sr_{0.4}Fe_{0.8}Co_{0.2}O_{3-\delta}$	800	330	[128]
$Sr_2Ni_{0.75}Mg_{0.25}MoO_{6-\delta}$	$La_{0.88}Sr_{0.12}Ga_{0.82}Mg_{0.18}O_{3-\delta}$ (700)/$Ce_{0.8}Sm_{0.2}O_{2-\delta}$	$La_{0.7}Sr_{0.3}Fe_{0.9}Co_{0.1}O_{3-\delta}$	800	429	[123]
$Sr_2Ni_{0.75}Mg_{0.25}MoO_{6-\delta}$	$La_{0.88}Sr_{0.12}Ga_{0.82}Mg_{0.18}O_{3-\delta}$ (500)/$Ce_{0.8}Sm_{0.2}O_{2-\delta}$	$La_2NiO_{4+\delta}$	800	276	[147]
$Sr_2Ni_{0.75}Mg_{0.25}MoO_{6-\delta}$	$La_{0.88}Sr_{0.12}Ga_{0.82}Mg_{0.18}O_{3-\delta}$ (500)/$Ce_{0.8}Sm_{0.2}O_{2-\delta}$	$La_{1.5}Ca_{0.5}Ni_{0.67}Fe_{0.33}O_{4+\delta}$	800	273	[147]
$Sr_2Ni_{0.7}Mg_{0.3}MoO_{6-\delta}$	$Ce_{0.8}Sm_{0.2}O_{2-\delta}/La_{0.8}Sr_{0.2}Ga_{0.8}Mg_{0.2}O_{3-\delta}$ (700)	$SmBaCo_2O_{5+\delta}$	800	160	[127]
$Sr_2Ni_{0.3}Mg_{0.7}MoO_{6-\delta}$	$Ce_{0.8}Sm_{0.2}O_{2-\delta}/La_{0.8}Sr_{0.2}Ga_{0.8}Mg_{0.2}O_{3-\delta}$ (700)	$SmBaCo_2O_{5+\delta}$	800	119	[127]
$Ba_{0.5}Sr_{0.5}Mo_{0.1}Fe_{0.9}O_{3-\delta}$	$La_{0.8}Sr_{0.2}Ga_{0.8}Mg_{0.2}O_{3-\delta}$ (150)	$Ba_{0.5}Sr_{0.5}Mo_{0.1}Fe_{0.9}O_{3-\delta}$	800	2280	[148]

One can see that the SOFCs’ power density tends to increase with a decrease in the electrolyte’s thickness (due to a corresponding decline in the ohmic resistance) despite the existence/absence of CeO_2-based buffer layers. Nevertheless, the performance of the compared SOFCs varies greatly, even for close electrolyte thicknesses, indicating that other functional components (cermets, oxygen electrodes) have a significant effect on the achievable output characteristics.

[131]					
$SrFe_{0.75}Mo_{0.25}O_{3-\delta}$	$La_{0.9}Sr_{0.1}Ga_{0.8}Mg_{0.2}O_{3-\delta}$ (30)	$SrFe_{0.75}Mo_{0.25}O_{3-\delta}$	800	703	[149]
$PrBa(Fe_{0.8}Sc_{0.2})_2O_{5+\delta}$	$La_{0.9}Sr_{0.1}Ga_{0.8}Mg_{0.2}O_{3-\delta}$ (275)	$PrBa(Fe_{0.8}Sc_{0.2})_2O_{5+\delta}$	800	713	[150]
$Sr_2Fe_{1.5}Mo_{0.5}O_{6-\delta}$-$La_{0.9}Sr_{0.1}Ga_{0.8}Mg_{0.2}O_{2.85}$	$La_{0.9}Sr_{0.1}Ga_{0.8}Mg_{0.2}O_{3-\delta}$ (10)	$Sr_2Fe_{1.5}Mo_{0.5}O_{6-\delta}$-$La_{0.9}Sr_{0.1}Ga_{0.8}Mg_{0.2}O_{3-\delta}$	700	880	[151]
$Pr_{0.6}Sr_{0.4}Fe_{0.8}Ni_{0.2}O_{3-\delta}$	$Ce_{0.8}Gd_{0.2}O_{2-\delta}/La_{0.9}Sr_{0.1}Ga_{0.8}Mg_{0.2}O_{3-\delta}$ (320)/$Ce_{0.8}Gd_{0.2}O_{1.9}$	$Pr_{0.6}Sr_{0.4}Fe_{0.8}Ni_{0.2}O_{3-\delta}$	800	500	[152]
$PrBaMn_{1.5}Fe_{0.5}O_{5+\delta}$	$La_{0.8}Sr_{0.2}Ga_{0.8}Mg_{0.2}O_{3-\delta}$ (520)	$PrBaMn_{1.5}Fe_{0.5}O_{5+\delta}$	800	540	[153]
$La_{0.5}Sr_{0.5}Fe_{0.9}Nb_{0.1}O_{3-\delta}$	$La_{0.82}Sr_{0.18}Ga_{0.83}Mg_{0.17}O_{3-\delta}$ (300)	$La_{0.5}Sr_{0.5}Fe_{0.9}Nb_{0.1}O_{3-\delta}$	750	630	[154]
$La_{0.54}Sr_{0.36}Co_{0.2}Fe_{0.6}Nb_{0.2}O_{3-\delta}$	$Ce_{0.8}Sm_{0.2}O_{2-\delta}/La_{0.9}Sr_{0.1}Ga_{0.8}Mg_{0.2}O_{3-\delta}$ (200)/$Ce_{0.8}Sm_{0.2}O_{1.9}$	$La_{0.54}Sr_{0.36}Co_{0.2}Fe_{0.6}Nb_{0.2}O_{3-\delta}$	800	539	[155]
$Sr_2TiFe_{0.9}Mo_{0.1}O_{6-\delta}$	$Ce_{0.8}Sm_{0.2}O_{2-\delta}/La_{0.9}Sr_{0.1}Ga_{0.8}Mg_{0.2}O_{3-\delta}$ (200)/$Ce_{0.8}Sm_{0.2}O_{1.9}$	$Sr_2TiFe_{0.9}Mo_{0.1}O_{6-\delta}$	800	444	[156]
$Sr_2Fe_{1.4}Nb_{0.1}Mo_{0.5}O_{6-\delta}$	$La_{0.8}Sr_{0.2}Ga_{0.83}Mg_{0.17}O_{3-\delta}$ (243)	$Sr_2Fe_{1.4}Nb_{0.1}Mo_{0.5}O_{6-\delta}$	800	531	[157]
$Sr_{0.95}Ti_{0.3}Fe_{0.63}Ni_{0.07}O_{3-\delta}$	$Ce_{0.6}La_{0.4}O_{2-\delta}/La_{0.8}Sr_{0.2}Ga_{0.83}Mg_{0.17}O_{3-\delta}$ (300)	$La_{0.6S}Sr_{0.4}Co_{0.2}Fe_{0.8}O_{3-\delta}$-$Gd_{0.1}Ce_{0.9}O_{2-\delta}$	800	1000	[132]

SOFC revealed no cracking, delamination or discontinuity. The polarization resistance of an anode-supported cell containing a $La_{0.9}Sr_{0.1}Ga_{0.8}Mg_{0.2}O_{3-\delta}$ film decreased from 0.41 to 0.05 Ω cm^2 as the temperature increased from 600 to 800 °C. The OCV and P_{max} values were in the range of 0.85–0.95 V and 650-1420 mW cm^{-2}, respectively, at a temperature range of 600–750 °C.

Combining the two approaches for SOFC design can be found in [138][139][140][141]. Bi et al. deposited a $Ce_{0.6}La_{0.4}O_{2-\delta}$(LDC)/LSGM bi-layer film on a Ni-$Ce_{0.9}Gd_{0.1}O_{2-\delta}$ anode. Therefore, the cell design allowed for high OCVs (1.02 and 1.043 V at 800 °C) and high power density values (1100 and 1565 mW cm^{-2} at 800 °C) to be achieved at a LDC/LSGM bi-layer thickness of 100 and 65 μm, respectively [138][139]. Ju et al. [141] reached a paramount performance of 1790 mW cm^{-2} at 700 °C for a SOFC based on an LSGM film with a thickness of 6 μm: this used an SDC buffer layer with a thickness of 500 nm, which was deposited on a Ni–Fe porous anode support. After a thermal cycle going from 700 to 25 °C, the fabricated cell showed an OCV of 1.1 V and P_{max} of 1620 mW cm^{-2}, which was almost the same as the first cycles.

According to a number of investigations [139][142][143][158], the most effective design for SOFCs composed of barrier layers is the LDC/LSGM/LDC tri-layered electrolyte. Bi et al. reported [139] that an anode-supported SOFC with an LDC/LSGM/LDC tri-layered electrolyte film significantly increased when using a cell with an LDC/LSGM bi-layered electrolyte film with the same thickness [138]. Guo et al. [143], depositing an LDC/LSGM/LDC tri-layer with thickness of 30 μm on a Ni-$Ce_{0.8}Sm_{0.2}O_{2-\delta}$ anode, fabricated a cell with a 75 mL min^{-1} H_2 flow rate that generated 1230 W cm^{-2} at 800 °C. The specific ohmic resistance across the LDC/LSGM/LDC tri-layer electrolyte film was measured to be equal to 0.086 Ω cm^2 at 800 °C. The obtained data showed that the polarization resistance was higher than the ohmic resistance at temperatures below 700 °C. A long-term stability experiment was performed on the aforementioned cell with a current density of 1000 mA cm^{-2} and a 30 mL min^{-1} H_2 flow rate at 800 °C. The results of 95 h-test demonstrated that the maximum power density values decreased from 1.08 to 0.81 W cm^{-2}.

Researchers of [143] suggest that there was little diffusion of the transition metal from the electrodes to the electrolyte during the test.

Serious efforts have been made to replace traditional cermet anodes with single-phase oxide materials: this is in an attempt to avoid chemical interactions. Complex oxides with double perovskite ($Sr_2MMoO_{6-\delta}$ (M = Mg, Ti, Ni, Fe) [120][122][127][128][146][147][151][156]), layered [150][153] and perovskite [132][149] structures were successfully tested as alternative anode materials for SOFCs with LSGM electrolytes. A buffer layer of doped ceria was used to avoid chemical interactions between an LSGM electrolyte and double perovskites [120][127][128], as well as between an LSGM electrolyte and an oxide cathode [123][147][159]. The composite electrodes $Sr_2Fe_{1.5}Mo_{0.5}O_{6-\delta}$-$La_{0.9}Sr_{0.1}Ga_{0.8}Mg_{0.2}O_{3-\delta}$ [151], $Sr_2CoMoO_{6-\delta}$-$La_{0.9}Sr_{0.1}Ga_{0.8}Mg_{0.2}O_{3-\delta}$ and $Sr_2Co_{0.9}Mn_{0.1}NbO_{6-\delta}$-$La_{0.9}Sr_{0.1}Ga_{0.8}Mg_{0.2}O_{3-\delta}$ [160] have been proposed to solve the thermo-mechanical incompatibility between an electrolyte and an electrode due to a mismatch in the materials' thermal expansion [134][142][143][144][151][160][161][162][163].

An analysis of recent studies illustrates that LSGM can be used as a base matrix for the formation of both composite electrodes and new composite electrolytes [160][164][165][166][167][168][169][170]. Xu et al. [160] fabricated a cell based on a $La_{0.9}Sr_{0.1}Ga_{0.8}Mg_{0.2}O_{3-\delta}$-$Ce_{0.8}Gd_{0.2}O_{1.9}$ electrolyte, with $Sr_2CoMoO_{6-\delta}$-$La_{0.9}Sr_{0.1}Ga_{0.8}Mg_{0.2}O_{3-\delta}$ as the anode and $Sr_2Co_{0.9}Mn_{0.1}NbO_{6-\delta}$-$La_{0.9}Sr_{0.1}Ga_{0.8}Mg_{0.2}O_{3-\delta}$ as the cathode. For this cell, obtained with a 95 wt.% $La_{0.9}Sr_{0.1}Ga_{0.8}Mg_{0.2}O_{3-\delta}$-5 wt.% $Ce_{0.8}Gd_{0.2}O_{2-\delta}$ electrolyte, the OCV, P_{max} and current density values at 800 °C were equal to 1.08 V, 192 mW cm^{-2}, and 720 mA cm^{-2}, respectively [160].

The electrochemical investigations in [171][172][173][174][175] for LSGM-based SOFCs confirm that these cells can operate in both fuel cell and electrolysis cell modes. Reversible cells were fabricated in [175] with NiO–YSZ-substrate as an anode, $La_{0.9}Sr_{0.1}Ga_{0.8}Mg_{0.2}O_{3-\delta}$ film as an electrolyte and $Sm_{0.5}Sr_{0.5}CoO_{3-\delta}$ as an air electrode. It was established that the infiltration of cerium nitrate into the substrate was an effective means of increasing cell performance. The maximum power density of this cell at 3 M Ce nitrate infiltration achieved 950 mW cm^{-2} at 600 °C.

5. Conclusions

Complex oxides based on $LaGaO_3$ offer a convenient basis for designing oxygen-conducting electrolytes that can be employed in intermediate-temperature solid oxide fuel cells (SOFCs). A rational combination of appropriate dopants incorporated at various sublattices of $LaGaO_3$ allows for co-doped derivatives ($La_{1-x}Sr_xGa_{1-y}Mg_yO_{3-\delta}$, LSGM) with superior transport properties. LSGM materials are considered one of the most conductive oxygen-ionic electrolytes, enabling a decrease in SOFC operation temperatures by 100–300 °C compared to YSZ-based SOFCs. As a result, very high SOFC performances (from 0.5 to 1.5 W cm^{-2} at 700 °C) were reported for lab-type electrochemical cells. However, to efficiently place laboratory studies on a manufacturing scale, several issues remain, including the development of simple and low-cost technologies for electrolyte preparation (including thin-film forms), searching for strategies to improve the chemical stability of LSGM with other SOFC components (especially, with nickel) and the design of new electrochemically active electrodes. In this regard, the studies serves as the starting point for further research in fields like solid state chemistry, physical chemistry, electrochemistry and the technology of $LaGaO_3$-based materials and electrochemical cells.

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