# A Critical Review on Materials for Solid Oxide Fuel Cell Components

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## ABSTRACT

Solid-oxide fuel cells are efficient devices for the conversion of chemical to electrical energy and a typical solid-oxide fuel cell consists of a solid electrolyte, cathode, and anode. In the last few decades, researchers have been working extensively on materials development for different components of these devices. In this review article, we briefly discuss the requirements for different components and review prominent materials families explored by the scientific community. As the search for greener energy alternatives such as solid-oxide fuel cells have intensified manifold due to the climate change emergency, a substantial literature was produced on the materials development of these devices and, therefore, we believe a brief review article dedicated to the same will be valuable for the scientific community, particularly new young entrant researchers in the field.

## 1. INTRODUCTION

Many electrochemical conversion and storage technologies such as Li-ion and solid-state batteries, fuel cells and capacitors are being heavily investigated to decarbonise our environment[1–8]. Fuel cells is one of the promising technologies and depending on the nature of the electrolyte used in the fuel cell there are various types of fuel cells: Solid Oxide Fuel Cell (SOFC), Molten Carbonate Fuel Cell (MCFC), Polymer Electrolyte (Proton Exchange) Membrane Fuel Cell (PEMFC), Phosphoric Acid Fuel Cell (PAFC), Direct Methanol Fuel Cell (DMFC) and Alkaline Fuel Cells (AFC). Broadly these fuel cell types can also be classified as high-temperature devices, such as SOFC and MCFC, and low-temperature devices such as PEMFC, PAFC, DMFC and AFC. The operating temperature of different fuel cell types tends to depend on the nature of the electrolyte being used and is also reflected in the applications of various fuel cell types.

SOFCs, in particular, have attracted much attention in recent times. This increased interest in SOFCs stems from the fact that SOFCs have many advantages over other types of fuel cells. The flexibility of fuel, which allows the use of hydrogen, carbon dioxide, methane, and other hydrocarbons to power the cells is certainly a primary one. Further benefits include higher efficiency, a step towards a hydrogen-based economy, low emissions, relatively low cost and scalability, which allows the stacking of a required number of individual cells in series depending on the amounts of power needed in a particular
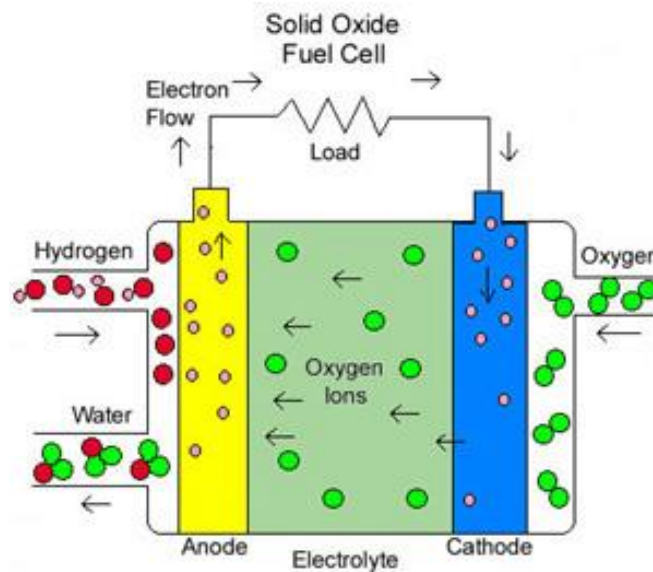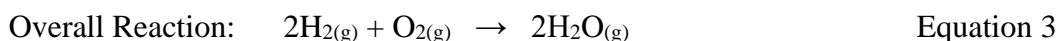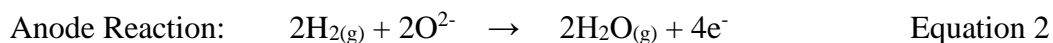


*Figure 1. Schematic diagram highlighting the key features of the operation
of a solid oxide fuel cell (reproduced with permission from reference 13).*

device. It is in this context that SOFCs have assumed prime importance among the different types of fuel cells and we, therefore, believe that a concise review article briefly discussing promising materials families in the field would be relevant for researchers in the field. For comprehensive long reviews, we invite the reader to cited review articles here[9–12].

A typical SOFC consists of a solid electrolyte, which separates the anode and cathode from each other. The cathode acts as a reduction site and reduces the oxygen being inserted into the system at the cathode site itself. The oxide ions migrate via the electrolyte to the anode where they oxidise the fuel, producing water, heat and more importantly electrons, to perform useful work (Figure 1)[13].

The oxygen reduction reaction (ORR) occurs at the cathode and the oxide ions produced are transported via an electrolyte to the anode (Equation 1). It is here at the anode site that the oxide ions react with fuel (hydrogen gas) to produce electrons (Equation 2). The electrons generated at the interface of the anode and electrolyte are transported to an external circuit for useful work through the anode. The electrons finally arrive at the cathode and continue the process[14].

$$\text{Cathode Reaction:} \quad O_{2(g)} + 4e^- \; \rightarrow \; 2O^{2-} \qquad\qquad \text{Equation 1}$$

$$\text{Anode Reaction:} \quad 2H_{2(g)} + 2O^{2-} \; \rightarrow \; 2H_2O_{(g)} + 4e^- \qquad\qquad \text{Equation 2}$$

$$\text{Overall Reaction:} \quad 2H_{2(g)} + O_{2(g)} \; \rightarrow \; 2H_2O_{(g)} \qquad\qquad \text{Equation 3}$$

Apart from the anode, cathode and electrolyte, an interconnect is used to connect the individual cells in series to generate useful amounts of power. In simple terms, the interconnect material is required to combine the current generated by individual cells, and thus should ideally possess good electronic conductivity. In addition, it should be chemically stable concerning both anode and cathode materials, and stable in both oxidising and reducing atmospheres. In the following sections of the paper, requirements for different components and prominent materials families fulfilling the said requirements will be reviewed in detail.

## 2. MATERIALS FOR CATHODES

The cathode, being the site for the oxygen reduction reaction (ORR), is highly instrumental in determining the performance of a cell. As electrons are necessary for the reduction of oxygen molecules, superior electronic conductivity of the cathode material is the primary requirement. Low or no chemical

reaction with other cell components, compatible thermal expansion coefficient (TEC), and high catalytic activity for the reduction of an oxygen molecule are other requirements for the cathode material. The porous microstructure of the cathode material further enhances the ORR as it ensures the access of oxygen molecules to the cathode surface, and thus extends the active region beyond the restricted triple phase boundary (TPB).

In pure electronic conducting cathode materials such as $La_{1-x}Sr_xMnO_{3-\delta}$ (LSM), ORR is limited to a very narrow TPB region, the air/cathode/electrolyte interface (Figure 2). The air/electrolyte interface is immaterial as far as the ORR rate is concerned because the commonly used electrolyte materials are catalytically inactive.

Although there is the technical possibility of ORR occurring at the air/cathode interface because of insignificant ionic conduction of pure electronic conductor cathode materials, the oxide ions produced fails to migrate to the anode for useful work. Thus, the practical region for the ORR to occur in such materials is a very narrow TPB. It is here that so-called mixed-ionic electronic conducting (MIEC) cathode materials assume crucial importance. The mixed conductivity of MIEC cathode materials lets the system to extend the otherwise narrow ORR region and thus increase the efficiency of the cell (Figure
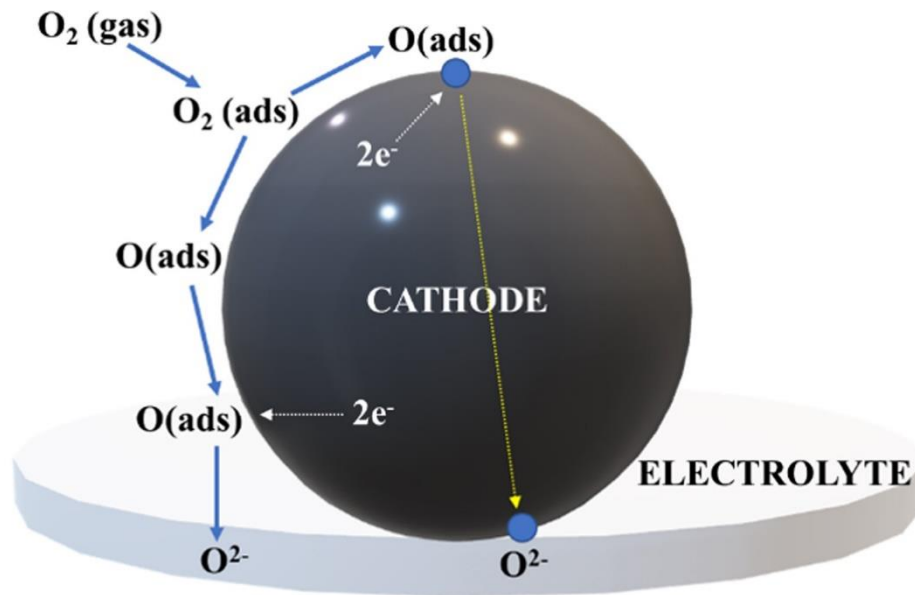


*Figure 2. Schematic representation of the oxygen reaction at MIEC cathode material (reproduced with permission from reference 15).*

2)[15–17]. In this regard, the last decade has seen significant research activity in developing MIEC materials for SOFC cathodes based on perovskites, double perovskites, Ruddlesden-Popper phases, and other layered oxide materials.

## 2.1 Substituted Lanthanum Manganite

In high-temperature SOFCs, $La_{1-x}Sr_xMnO_{3-\delta}$ (LSM), has been the material of choice for cathodes and has thus been explored extensively[18,19]. The material adopts the perovskite structure and doping with strontium replaces lanthanum in the structure and enhances the electronic conductivity of the material by increasing the hole carriers[20]. Doping the material with Sr results in the oxidation of $Mn^{3+}$ to $Mn^{4+}$ and leaves the oxygen content of the material intact. Thus, the material achieves a superior electronic conductivity, in the range of 200 - 300 $Scm^{-1}$ at 900 °C[18]. But because of the limits imposed by either reactivity with other cell components and/or TEC compatibility, the doping level is usually kept under 30 mol percent[21]. On increasing Sr levels beyond this limit, TEC incompatibility[19] and reactions with other cell components such as the formation of $SrZrO_3$ and $La_2Zr_2O_7$ with YSZ electrolyte have been observed[22,23].

*Table 1. Properties of some relevant SOFC cathode materials.*

| Material composition | Total conductivity (S/cm) | Ionic conductivity (S/cm) | TEC (x $10^{-6}$ °$C^{-1}$) |
|---|---|---|---|
| $LaMnO_3$ | 71 (700 °C)[24] | - | 9.5-10.75 (25 - 1000 °C)[25] |
| $La_{0.8}Sr_{0.2}MnO_{3-\delta}$ | 150(500 °C)[26] | 4.2 x $10^{-10}$ (750 °C)[27] | 11.8 (30 - 1000°C)[26] |
| $La_{0.6}Sr_{0.4}MnO_{3-\delta}$ | 125 (700 °C)[28] | - | 11.7-12.2 (25 - 1000°C)[29] |
| $La_{0.6}Sr_{0.4}CoO_{3-\delta}$ | 1084 (1000 °C)[30] | 0.22 (800 °C)[31] | 20.5 (30-1000 °C)[31] |
| $La_{0.8}Sr_{0.2}CoO_{3-\delta}$ | 1291 (1000 °C)[30] | 4.9 x $10^{-4}$ (750 °C)[32] | 19.7 (100 – 900 °C)[33] |
| $La_{0.6}Sr_{0.4}Co_{0.2}Fe_{0.8}O_{3-\delta}$ | 320 (700 °C)[33] | 8 x $10^{-3}$ (800 °C)[31] | 15.3 (100 -600°C)[33] |
| $La_2NiO_{4+\delta}$ | 85 (700 °C)[34] | 4 x $10^{-2}$ (800°C)[35] | 13.8 (75 – 900 °C)[36] |
| $La_4NiO_{10\pm\delta}$ | 87 (800 °C)[37] | - | 11.5 (250 – 800°C)[38] |
| $Pr_4NiO_{10\pm\delta}$ | 90 (600 °C)[39] | - | 12 (25 – 1000 °C)[39] |

The major challenge, however, with LSM as a cathode has been its poor oxide-ion conductivity, of the order of $10^{-7}$ - $10^{-8}$ S $cm^{-1}$ at 800 °C[40]. The formation of a composite of LSM with a material of high ionic conductivity has been explored in the hope that this limitation of low ionic conductivity could be

resolved[41]. Ostergard *et al.* by using the composites of LSM+YSZ reduced area specific resistance (ASR) from 2.7 $\Omega cm^2$ obtained by using pure LSM to 0.5 $\Omega cm^2$ for an LSM+YSZ composite operating at 1000 °C[41]. However, because of long-term thermal and mechanical degradation problems with LSM cathode materials and their low inherent oxide ion conductivity, a search for better materials for IT-SOFCs continues. The problem arises from the fact that at high operating temperatures polarisation losses are negligible but once the temperature is lowered to the intermediate range, polarisation losses become significant and thus negatively impact the cell efficiency by decreasing the kinetics associated with ORR and charge transport at the cell cathode. The cathode materials based on LSM further suffer from a severe deleterious problem of strontium segregation, which will be discussed later.

## 2.2 Substituted Lanthanum Cobaltite

$LaCoO_3$ is again a perovskite like LSM and possesses better electronic conductivity than LSM[42]. The main problem, however, has been the stability[19] of this material which has been tackled by doping the system with Sr which replaces Ln in the structure to give the strontium-substituted cobaltite perovskites (LSC: $La_{1-x}Sr_xCoO_{3-\delta}$)[43]. LSC is a mixed conductor material and has shown good ionic conductivity and ORR catalytic properties[44–46]. The major issue with LSC, however, is its high TEC, of the order of $20 \times 10^{-6} K^{-1}$. When this considerably high TEC is compared to the commonly used electrolytes like YSZ and CGO (~$12 \times 10^{-6} K^{-1}$), compatibility issues with other cell components come to the fore and render the material problematic[47,48].

It has been reported that the high TEC of LSC cathodes originates from octahedrally-coordinated cobalt ion transitions between low- and high-spin states of the $Co^{3+}$ $3d^6$ ion[48]. In light of this knowledge, Co has been substituted with Fe to produce the state of art cathode material, $La_{1-x}Sr_xCo_{1-y}Fe_yO_{3-\delta}$ (LSCF). $La_{0.6}Sr_{0.4}Co_{0.2}Fe_{0.8}O_{3-\delta}$ (LSCF6428) is the most promising and studied composition of these materials. The electronic conductivity of this material is significant, ranging from 350 to 250 $Scm^{-1}$ in 600 - 800 temperature range°C[47]. This significant electronic conductivity of the material originates from the mixed valencies $Fe^{3+}/Fe^{4+}$ and $Co^{3+}/Co^{4+}$, which is essentially the result of La substitution by Sr. Equally important benefit of this substitution is the formation of oxygen vacancies in the LSCF system, which ultimately contributes to the ionic conductivity of this MIEC cathode material, with $10^{-2}$ $Scm^{-1}$ ionic conductivity at 800 °C being reported by Teraoka *et al.* [49]. Further the material also has TEC in the range of 15 x $10^{-6} K^{-1}$, which is in the compatible range of other cell components[47].

The primary limitation of LSCF6428 occurs when it is used with the commonly used electrolyte because it reacts with YSZ and negatively impacts cell performance with time. This reduces the flexibility of this promising cathode material, and thus it has primarily been used with the CGO electrolyte, with which it, fortunately, does not react[50]. However, because of the common use of the YSZ electrolyte, several attempts have been made to make LSCF6428 workable with YSZ. A common approach to tackle deleterious reactivity has been to incorporate the ceria barrier layer between the electrolyte and cathode[51,52]. This has also helped in improving the relatively higher ASR that pure LSCF affords, 0.3 $\Omega cm^2$ at 700 °C[53], which is well above the target value of 0.15 $\Omega cm^2$.[54] Dusastre *et al.* reduced the ASR of pure LSCF by making composites of LSCF with CGO, reporting an ASR of 0.16 $\Omega cm^2$ at 700 °C, almost halving the polarisation resistance[55]. Wang and Mogensen reduced it further to the remarkable value of 0.026 $\Omega cm^2$ at 700 °C with CGO and 0.12 $\Omega cm^2$ at 700 °C with YSZ electrolyte coated with a thin layer of CGO[56]. But because of the complexity associated with the use of composites as cathodes, there is the possibility of a reaction between CGO and YSZ to form the less ionic conducting phase, (Ce, Zr, Gd, Y)$O_{2-\delta}$ and it has been reported that such phases are formed and are responsible for reducing the cell performance.[57]

Above all, the main problem with the promising LSCF cathode materials is their degradation with time during cell operation. This problem chiefly manifests itself in strontium segregation and chromium poisoning. Both of these problems drastically reduce cell performance. When in operation, Sr selectively segregates towards the cell surface to form a SrO layer at the cathode surface, which effectively stops the ORR from occurring at the air/cathode interface[58,59]. The chromium poisoning problem emanates from the necessity of using interconnects to connect the individual cells in series to generate the required amounts of power for practical purposes. The commonly used material for interconnects contains chromium, and it vaporises during cell operation. The harmful impact of chromium vapours comes from its deposition on cathode materials, thereby degrading their performance with time[60].

There have been various attempts to resolve this cathode degradation but not with profound success yet. Use of electrical polarisation to de-segregate the strontium[61,62] and use of acid-etching to reduce the formation of passivating (Ce, Zr, Gd, Y)$O_{2-\delta}$ layers[59,63] and also an attempt to stop Cr poisoning by coating[64] the steel interconnects have been used but with less success.

Another related cathode composition is the doped lanthanum ferrite; $La_xSr_{1-x}Fe_yNi_{1-y}O_{3-\delta}$ (LSFN), with $La_{0.6}Sr_{0.4}Fe_{0.8}Ni_{0.2}O_{3-\delta}$ (6428) as the optimum composition. The material shows electronic conductivity

of 300 Scm$^{-1}$ at 900 °C with a reasonable TEC of $14 \times 10^{-6}$ K$^{-1}$,[65] but they also come with their problems of forming insulating phases such as $La_2Zr_2O_7$ and $SrCoO_3$ at the interface when used with YSZ as an electrolyte, which further degrades the performance of the cell.

Another class of materials, derived from the perovskite structure are the oxide materials known as double perovskites with the general formula $AA'B_2O_{5+\delta}$ where A is a rare earth cation, A' is an alkaline earth metal cation and B is a transition metal cation. In these phases, there is cation ordering of the rare earth and alkaline earth metal layers along the (001) axis. This leads to a doubling of the c parameter when compared to the c parameter of the parent perovskite phase[66]. The material further is an oxygen-deficient system with oxygen vacancies mainly located in the rare-earth layer. Two compositions, in particular, $GdBaCo_2O_{5+\delta}$ (GBCO) and $PrBaCo_2O_{5+\delta}$ (PBCO), have been studied extensively[67–70]. The materials have MIEC properties but suffer from relatively lower performance and thus composites of GBCO too have been developed for increased electrochemical performance[71].

LSCF is the most promising material for IT-SOFC cathodes but because of the degradation issues and strontium segregation discussed earlier, the search for alternative IT-SOFC cathode materials continues. One family suggested as potential IT-SOFC cathodes are the Ruddlesden-Popper phase materials. One of the materials of this family, $La_2NiO_{4+\delta}$ adopts the $K_2NiF_4$-tye structure and has been widely studied because of its remarkable oxide ion conductivity.

## 2.3 Ruddlesden-Popper Phases

S.N. Ruddlesden and P. Popper reported a new class of materials with the overall formula of $A_{n+1}BnO_{3n+1}$, in 1958[72]. The structure consists of $nABO_3$ perovskite layers alternating between two AO rock-salt layers[73] and the number of perovskite polyhedral units packed between rock-salt units of the structure decides the phase of the material (Figure 3)[74]. Since the perovskite structure allow accommodating oxygen defects and Ruddlesden-Popper (RP) phases contain perovskite layer/s in their structure, it is one of the reasons behind the expectation that these materials could work as promising oxygen conductors. It indeed has been found to be true; it is the unique structural features of lower-order phases such as $La_2NiO_{4+\delta}$ (LNO), $Pr_2NiO_{4+\delta}$ (PNO) and $Nd_2NiO_{4+\delta}$ (NNO) which permit them to accommodate a substantial amount of interstitial oxygen defects. Ruddlesden-Popper phases materials further take care of strontium segregation problem – a main problem associated with the state-of-art LSCF cathode

materials – because Ruddlesden-Popper phases are composed of different constituents and do not necessarily contain Sr.
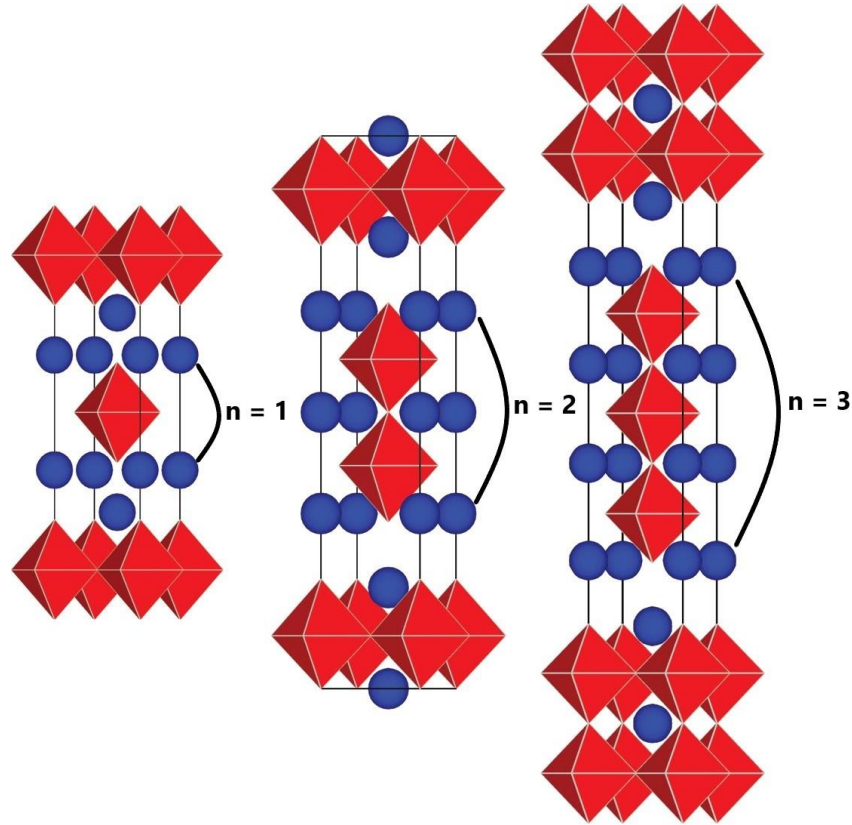


*Figure 3. Simplified illustration of Ruddlesden-Popper phase's structure. The number of perovskite layers sandwiched defines the phase of the material (adapted from reference 74).*

Lower order n = 1 Ruddlesden-Popper phase materials have a robust capability of storing a considerable amount of interstitial oxygen in their structure which bestowed the materials with significant oxide ion conductivity. This renders the materials MIEC at intermediate temperatures which is the main motivation of intense research focus on these materials[75,76]. Thus n = 1 phases such as LNO, PNO and NNO have been studied extensively. With the lower-order phases such as LNO and PNO, the main issue though is the phase stability under operating conditions, which unfortunately restricts their use as IT-SOFC cathodes[37,77–81]. Even doped lower-order phases such as cobalt doped LNO, $La_2Ni_{0.9}Co_{0.1}O_{4+\delta}$, studied by Amow and co-workers observed extensive decomposition[80].

The impurity $Ni^{2+}/Ni^{3+}$ phase formation at high-temperatures in the n = 1 R-P phase originates from the In stoichiometric $La_2NiO_4$ is, Ni exists mainly in $Ni^{2+}$ state, which is stable only at temperatures over 1100 °C[82] but in higher order phases Ni tend to be predominantly in $Ni^{3+}$ state, which is favourably stable

below 900 °C. Therefore, higher-order phases such as $La_4Ni_3O_{9.78}$ (L4N3), $Pr_4Ni_3O_{10\pm\delta}$ (P4N3) and $La_2Pr_2Ni_3O_{10\pm\delta}$ (L2P2N3) comprising predominantly of $Ni^{3+}$, expectedly offer long-term stability[83].

This was confirmed by Skinner and co-workers who observed that higher-order phases show increased stability with no impurity phase appearing after 2 weeks of heating of n = 2 and 3 phases at 900°C unlike lower-order phases which show an impurity phase[82]. While this is promising and has been confirmed by several studies[13,78,79,83–87] but we are leaving discussion on Ruddlesden-Popper phase materials limited here and readers are invited to read the dedicated review on the cathode application of these materials published recently by M. Yatoo and S. Skinner[88].

## 3. MATERIALS FOR ELECTROLYTES

The electrolyte for SOFCs is a dense ceramic material. It is through this ceramic layer that oxide ions migrate to the anode site, and thus the primary requirement for electrolyte materials is that they should display very good oxide ion conductivity. The internal resistance of an electrolyte material to oxide ion transport and the distance to be travelled by oxide ions from cathode to anode is of utmost importance as far as material performance is concerned.

Further, to avoid losses and thus have better efficiency, electrolyte materials ideally should have zero electronic conductivity so that electrons generated through the anode reaction are not transported through the electrolyte to the cathode to short-circuit the cell. Further, it should be unreactive with electrode materials and have a matching TEC with that of other components of the cell.

The electrolyte for SOFCs is a dense ceramic material. It is through this ceramic layer that oxide ions migrate to the anode site, and thus the primary requirement for electrolyte materials is that they should display very good oxide ion conductivity. Yttria stabilised zirconia, $ZrO_2$-$Y_2O_3$ (YSZ) is the most common electrolyte material for SOFCs[18,42]. It has good mechanical properties and is chemically stable over a wide range of operating temperatures and oxygen partial pressures. The material is composed of $ZrO_2$, which is stabilised by $Y_2O_3$ or other dopants like MgO and $Sc_2O_3$[42,89]. The ionic conductivity of this electrolyte material depends on the nature and amount of dopant being used because it is these dopants which create oxygen vacancies in zirconia, which in turn are responsible for oxide ion conduction in the electrolyte[42,89,90].

However, the formation of insulating phases at operating temperatures when YSZ electrolyte is used with common cathode materials such as LSC, LSCM and LSCF, brings chemical stability issues into the picture; and because insulating phases like $SrZrO_3$ and $La_2Zr_2O_7$ have less ionic conductivity than electrolyte material, the cell performance is reduced with time[90–94].



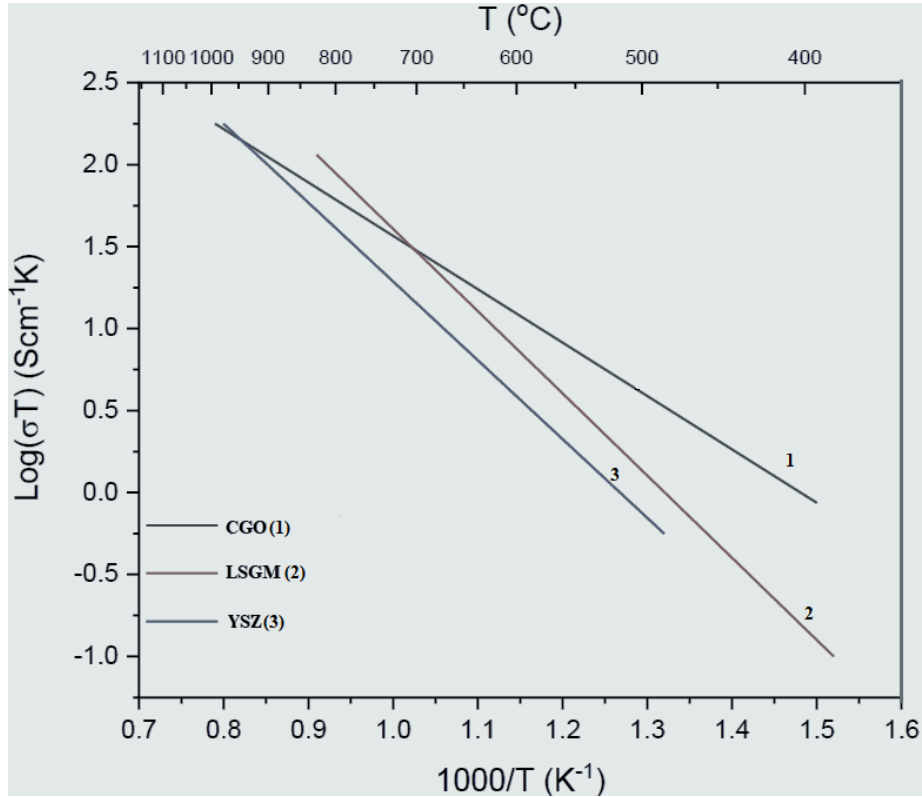*Figure 4. Comparison of ionic conductivity of three main electrolyte materials.*

Ceria ($CeO_2$) doped with gadolinium ions ($Gd^{3+}$) has been found to be promising in terms of its ionic conductivity for use as a SOFC electrolyte. $Ce_{0.9}Gd_{0.1}O_{1.95}$ (CGO10) composition has been found to have better ionic conduction than YSZ[95,96]. The TEC of CGO10 is $13.5 \times 10^{-6} K^{-1}$, thus making it compatible with other cell components[97]. However, in CGO electrolytes under anodic conditions at operating temperatures, $Ce^{4+}$ ions are reduced to $Ce^{3+}$ ions and this is responsible for n-type electronic conduction, which short circuits the cell, thereby reducing the performance[96,98].

Recently magnesium-doped lanthanum gallate, $La_xSr_{1-x}Ga_yMg_{1-y}O_{3-\delta}$ (LSGM) because of its good ionic conductivity has been used as an electrolyte. This material exhibits excellent oxide ion conductivity in the intermediate temperature range and thus is suitable for studies where the goal is to develop materials

for IT-SOFCs such as this work[99]. The origin of this superior ionic conductivity is the vacancies created in the perovskite structure of lanthanum gallate ($LaGaO_3$) by doping strontium and magnesium at A and B sites respectively. In particular, two main compositions being used by researchers are $La_{0.8}Sr_{0.2}Ga_{0.8}Mg_{0.2}O_{3-\delta}$ (LSGM8282) and $La_{0.9}Sr_{0.1}Ga_{0.8}Mg_{0.2}O_{3-\delta}$ (LSGM9182). LSGM8282 presents the best ionic conductivity of 0.14 $Scm^{-1}$ at 700 °C as compared to the relatively lower value of 0.12 $Scm^{-1}$ at the same temperature[100]. These materials further show compatible TEC $\sim 12.0 \times 10^{-6}$ $K^{-1}$ and are thus widely used as electrolytes in IT-SOFCs research. Figure 4 demonstrates the comparison of ionic conductivity of the three conventional electrolyte materials discussed[101].

## 4. MATERIALS FOR ANODES

The primary role of anode material in a cell is to catalyse the fuel oxidation and then to conduct the electrons generated by the oxidation of fuel to the external circuit for useful work. Thus, a typical anode material should possess the good catalytic activity and electronic conductivity. It should also have good ionic conductivity for conducting oxide ions. Furthermore, the ability of the anode material to catalyse fuel oxidation assumes significance as far as cell efficiency is concerned.

A typical anode material should possess good catalytic activity and electronic conductivity to sufficiently fulfil its primary role to catalyse the fuel oxidation and then to conduct the electrons generated by oxidation of the fuel to the external circuit for useful work. Nickel is a good conductor and further acts as a catalyst for hydrogen oxidation but because it high TEC it is not mechanically compatible with electrolytes such as YSZ[102]. Therefore, nickel on its own as anode is avoided but is used in the form of a composite.

A recent trend in developing anode materials is to have MIEC materials with a porous structure. Nickel, because of its good catalytic properties and economic viability is the most common material used for anodes[18]. Ni dispersed over YSZ is thus the most commonly used anode material[103] and there are also reports where cermets of Ni with ceria doped with gadolinia – that is Ni-CGO – outperform the Ni-YSZ anode[104]. The main problem with Ni-YSZ is that it suffers from carbon deposition and sulphur poisoning which negatively impacts the electrochemical performance of the devices based on this anode. Despite the shortcomings, Ni-YSZ is a state-of-the-art anode for high-temperature SOFCs because of its high electrochemical activity and mechanical stability.

For intermediate temperature SOFCs, however, Ni-CGO is the popular anode material. While CGO on its own lacks electronic conductivity – which is therefore compensated by addition of Ni – it shows high ionic conductivity[105]. A further drawback of Ni-CGO anode is its mechanical strength, but it shows reduced carbon deposition when used with hydrocarbon fuels and therefore is a vital alternative to Ni-YSZ based anode materials[106]. The anode, however, is relatively less significant than the electrolyte and cathode because of its less limiting role in cell performance.

## 5. CONCLUSIONS

Arguably the most significant series of conferences – the United Nations Climate Change Conference – was recently concluded in Sharm El Sheikh, Egypt. More commonly referred to as the Conference of the Parties (COP), it is the 27th edition (COP27) and lays bare the significance of the devastating impact of fossil fuels on our environment. In this context technologies such as SOFCs assume central importance and, therefore, require a particular focus by scientists and technologists. Advancement in the search for new materials is one way to solve the challenges faced by energy storage and conversion technologies and SOFCs is one such technology where advancement in materials has proved critical. There are further many opportunities to develop layered oxide materials such as perovskites, double perovskites and Ruddlesden-Popper phase materials, including the development of composite electrodes for both fuel cell and electrolysis modes of operation. In this review article, we discussed the prominent materials families currently being investigated by the SOFCs community for different components of SOFCs and we believe that looking for new materials families and improving the performance of already identified materials will be instrumental in further developing the SOFCs technology.

# REFERENCES

1  C. Y. Wang, T. Liu, X. G. Yang, S. Ge, N. V Stanley, E. S. Rountree, Y. Leng and B. D. Mccarthy, *Nature*, 2022, **611**, 485.

2  G. Wang, L. Zhang and J. Zhang, *Chem. Soc. Rev*, 2012, **41**, 797–828.

3  P. Simon and Y. Gogotsi, *Nat Mater*, 2008, **7**, 845–854.

4  Baboo, J. P.; Yatoo, M. A.; Dent, M.; Hojaji Najafabadi, E.; Lekakou, C.; Slade, R.; Hinder, S. J.; Watts, J. F. Exploring Different Binders for a LiFePO4 Battery, Battery Testing, Modeling and Simulations. Energies **2022,** 15, 2332,  DOI: 10.3390/en15072332

5  Baboo, J. P; Jakubczyk, E; Yatoo, M. A; Phillips, M; Grabe, S; Dent, M; Hinder S; Watts, J and Lekakou, C; *J Power Sources* **2023,** 561, 232762, DOI 10.1016/j.jpowsour.2023.232762

6  Poonam, K. Sharma, A. Arora and S. K. Tripathi, *J Energy Storage*, 2019, **21**, 801–825.

7  Z. Ahmad, W. Kim, S. Kumar, T. H. Yoon and J. S. Lee, *ACS Applied Energy Materials,* 2020, **3,** 6743-6751.

8  G. Kaur, *Intermediate Temperature Solid Oxide Fuel Cells: Electrolytes, Electrodes and Interconnects*, Elsevier Science, 2019. DOI: 10.1016/C2018-0-00575-7

9  M. Singh, D. Zappa and E. Comini, *Int J Hydrogen Energy*, 2021, **46**, 27643–27674.

10  C. Sun, R. Hui and J. Roller, *Journal of Solid State Electrochemistry,* 2010, **14**, 1125-1144,

11  N. H. Menzler, F. Tietz, S. Uhlenbruck, H. Peter Buchkremer and D. Stöver, *Journal of Materials Science,* 2010, **45**, 3109-3135.

12  S. C. Singhal, *Solid State Ion*, 2000, **135**, 305–313.

13  P. V. Vibhu, PhD Thesis, University of Bordeaux, 2016.

14  A. Lashtabeg and S. J. Skinner, *J Mater Chem*, 2006, **16**, 3161–3170.

15  J. T. S. Irvine, D. Neagu, M. C. Verbraeken, C. Chatzichristodoulou, C. Graves and M. B. Mogensen, *Nat Energy*, 2016, **1**, 15014.

16  A. Grimaud, F. Mauvy, J. Marc Bassat, S. Fourcade, M. Marrony and J. Claude Grenier, *J Mater Chem*, 2012, **22**, 16017–16025.

17  N. N. M. Tahir, N. A. Baharuddin, A. A. Samat, N. Osman and M. R. Somalu, *J Alloys Compd*, 2022, **894**, 162458.

18  N. Q. Minh and T. Takahashi, *Science and Technology of Ceramic Fuel Cells*, Elsevier Science Ltd, Oxford, 1995.

19  N. Q. Minh, *Journal of the American Ceramic Society*, 1993, **76**, 563–588.

20  B. A. Boukamp, *Nat Mater*, 2003, **2**, 294.

21  C. Sun, R. Hui and J. Roller, *Journal of Solid State Electrochemistry*, 2010, **14**, 1125–1144.

22  H. Yokokawa, N. Sakai, T. Kawada and M. Dokiya, *Solid State Ion*, 1992, **52**, 43–56.

23  H. Taimatsu, K. Wada, H. Kaneko and H. Yamamura, *Journal of the American Ceramic Society*, 1992, **75**, 401–405.

24  J. Mizusaki, Y. Yonemura, H. Kamata, K. Ohyama, N. Mori, H. Takai, H. Tagawa, M. Dokiya, K. Naraya, T. Sasamoto, H. Inaba and T. Hashimoto, *Solid State Ion*, 2000, **132**, 167–180.

25  A. Hammouche, E. Siebert and A. Hammou, *Mater Res Bull*, 1989, **24**, 367–380.

26  F. Tietz, I. Arul Raj, M. Zahid and D. Stöver, *Solid State Ion*, 2006, **177**, 1753–1756.

27    B. Guan, W. Li, X. Zhang, A. Wedig, R. Merkle, J. Maier, S. Stämmler, B. Stuhlhofer, J. Hwang, Y. Ando and S. Watanabe, *ECS Transactions,* 2015, **68,** 549-556.

28    T. Ishiham, T. Kudo, H. Matsuda and Y. Takita, *Journal of the American Ceramic Society,* 1994, 77, 1682-1684.

29    A. Hammouche, E. Siebert and A. Hammou, *Mater Res Bull*, 1989, **24**, 367–380.

30    A. Petric, P. Huang and F. Tietz, *Solid State Ion*, 2000, **135**, 719–725.

31    H. Ullmann, N. Trofimenko, F. Tietz, D. Stöver and A. Ahmad-Khanlou, *Solid State Ion*, 2000, **138**, 79–90.

32    J. Hwang, Y. Ando and S. Watanabe, *ECS Trans*, 2015, **68**, 549–556.

33    L. W. Tai, M. M. Nasrallah, H. U. Anderson, D. M. Sparlin and S. R. Sehlin, *Solid State Ion*, 1995, **76**, 273–283.

34    D. ping Huang, Q. Xu, F. Zhang, W. Chen, H. xing Liu and J. Zhou, *Mater Lett*, 2006, **60**, 1892–1895.

35    H. Zhao, F. Mauvy, C. Lalanne, J. M. Bassat, S. Fourcade and J. C. Grenier, *Solid State Ion*, 2008, **179**, 2000–2005.

36    G. Amow, J. Au and I. Davidson, *Solid State Ion*, 2006, **177**, 1837–1841.

37    G. Amow, I. Davidson and S. Skinner, *Solid State Ion*, 2006, **177**, 1205–1210.

38    R. K. Sharma, M. Burriel, L. Dessemond, J.-M. Bassat and E. Djurado, *J Power Sources*, 2016, **325**, 337–345.

39    V. Vibhu, A. Rougier, C. Nicollet, A. Flura, S. Fourcade, N. Penin, J.-C. Grenier and J.-M. Bassat, *J Power Sources*, 2016, **317**, 184–193.

40    J. Fleig, *Annu Rev Mater Res*, 2003, **33**, 361–382.

41    M. J. L. Østergård, C. Clausen, C. Bagger and M. Mogensen, *Electrochim Acta*, 1995, **40**, 1971–1981.

42    O. Yamamoto, Y. Arachi, H. Sakai, Y. Takeda, N. Imanishi, Y. Mizutani, M. Kawai and Y. Nakamura, *Ionics (Kiel)*, 1998, **4**, 403–408.

43    A. Petric, P. Huang and F. Tietz, *Solid State Ion*, 2000, **135**, 719–725.

44    A. v Berenov, A. Atkinson, J. A. Kilner, E. Bucher and W. Sitte, *Solid State Ion*, 2010, **181**, 819–826.

45    S. R. Sehlin, H. U. Anderson and D. M. Sparlin, *Solid State Ion*, 1995, **78**, 235–243.

46    A. N. Petrov, O. F. Kononchuk, A. v Andreev, V. A. Cherepanov and P. Kofstad, *Solid State Ion*, 1995, **80**, 189–199.

47    L. W. Tai, M. M. Nasrallah, H. U. Anderson, D. M. Sparlin and S. R. Sehlin, *Solid State Ion*, 1995, **76**, 259–271.

48    M. A. Señarís-Rodríguez and J. B. Goodenough, *J Solid State Chem*, 1995, **118**, 323–336.

49    Y. Teraoka, H. M. Zhang, K. Okamoto and N. Yamazoe, *Mater Res Bull*, 1988, **23**, 51–58.

50    L. Qiu, T. Ichikawa, A. Hirano, N. Imanishi and Y. Takeda, *Solid State Ion*, 2003, **158**, 55–65.

51    W.-H. Kim, H.-S. Song, J. Moon and H.-W. Lee, *Solid State Ion*, 2006, **177**, 3211–3216.

52    S. P. Simner, J. P. Shelton, M. D. Anderson and J. W. Stevenson, *Solid State Ion*, 2003, **161**, 11–18.

53    J. M. Ralph, A. C. Schoeler and M. Krumpelt, *J Mater Sci*, 2001, **36**, 1161–1172.

54    B. C. H. Steele, *Solid State Ion*, 2000, **134**, 3–20.

55    V. Dusastre and J. A. Kilner, *Solid State Ion*, 1999, **126**, 163–174.

56    W. G. Wang and M. Mogensen, *Solid State Ion*, 2005, **176**, 457–462.

57    A. Tsoga, A. Gupta, A. Naoumidis and P. Nikolopoulos, *Acta Mater*, 2000, **48**, 4709–4714.

58    S. P. Simner, M. D. Anderson, M. H. Engelhard and J. W. Stevenson, *Electrochemical and Solid-State Letters*, 2006, **9**, A478–A481.

59    N. Miura, Y. Okamoto, J. Tamaki, K. Morinaga and N. Yamazoe, *Solid State Ion*, 1995, **79**, 195–200.

60    X. Li, J.-W. Lee and B. N. Popov, *J Power Sources*, 2009, **187**, 356–362.

61    F. S. Baumann, J. Fleig, M. Konuma, U. Starke, H.-U. Habermeier and J. Maier, *J Electrochem Soc*, 2005, **152**, A2074–A2079.

62    M. Finsterbusch, A. Lussier, J. A. Schaefer and Y. U. Idzerda, *Solid State Ion*, 2012, **212**, 77–80.

63    W. Wang and S. P. Jiang, *Solid State Ion*, 2006, **177**, 1361–1369.

64    Z. Lu, J. Zhu, Y. Pan, N. Wu and A. Ignatiev, *J Power Sources*, 2008, **178**, 282–290.

65    J. N. Audinot, Phd Thesis, University of Bordeaux, 1999.

66    S. A. Speakman, R. D. Carneim, E. A. Payzant and T. R. Armstrong, *J Mater Eng Perform*, 2004, **13**, 303–308.

67    A. Tarancon, M. Burriel, J. Santiso, S. J. Skinner and J. A. Kilner, *J Mater Chem*, 2010, **20**, 3799–3813.

68    A. A. Taskin, A. N. Lavrov and Y. Ando, *Phys Rev B*, 2005, **71**, 134414.

69    A. A. Taskin, A. N. Lavrov and Y. Ando, *Progress in Solid State Chemistry*, 2007, **35**, 481–490.

70    G. Kim, S. Wang, A. J. Jacobson, L. Reimus, P. Brodersen and C. A. Mims, *J Mater Chem*, 2007, **17**, 2500–2505.

71    M. H. Ko, Y. S. Yoo and J.-H. Hwang, *Ceram Int*, 2015, **41**, 4616–4620.

72    S. N. R. and P. Popper, *Acta Cryst.*, 1958, **11**, 54–55.

73    B. V. Beznosikov and K. S. Aleksandrov, *Crystallography Reports*, 2000, **45**, 792–798.

74    R. G. Palgrave, P. Borisov, M. S. Dyer, S. R. C. Mcmitchell, G. R. Darling, J. B. Claridge, M. Batuk, H. Tan, H. Tian, J. Verbeeck, J. Hadermann and M. J. Rosseinsky, *Journal of the American Chemical Society,* 2012, **134,** 7700-7714.

75    V. V. Kharton, A. P. Viskup, E. N. Naumovich and F. M. B. Marques, *J Mater Chem,* 1999, **9**, 2623–2629.

76    J. A. Kilner. S.J. Skinner, *Solid State Ion*, 2000, **135**, 709–712.

77    G. Amow, I. Davidson and S. Skinner, in *Proceedings of the Electrochemical Society SOFC-IX*, Proceedings of the Electrochemical Society SOFC-IX, 2005, 1745.

78    J.-M. Bassat, V. Vibhu, C. Nicollet, A. Flura, S. Fourcade, J.-C. Grenier and A. Rougier, *ECS Trans*, 2017, **78**, 655–665.

79    V. Vibhu, J.-M. Bassat, A. Flura, C. Nicollet, J.-C. Grenier and A. Rougier, *ECS Trans*, 2015, **68**, 825–835.

80 G. Amow, P. S. Whitfield, I. J. Davidson, R. P. Hammond, C. N. Munnings and S. J. Skinner, *Ceram Int*, 2004, **30**, 1635–1639.

81 G. Amow and S. J. Skinner, *Journal of Solid State Electrochemistry*, 2006, **10**, 538–546.

82 C. Munnings, S. Skinner, G. Amow, P. Whitfield and I. Davidson, *Solid State Ion*, 2006, **177**, 1849–1853.

83 Yatoo, M. A; PhD Thesis, Imperial College London, **2019.** DOI: 10.25560/89551

84 Yatoo, M. A.; Aguadero, A.; Skinner, S. J. LaPr$_3$Ni$_3$O$_{9.76}$ as a candidate solid oxide fuel cell cathode: Role of microstructure and interface structure on electrochemical performance. *APL Mater.* **2019**, *7*, 13204, DOI: 10.1063/1.5050249

85 Yatoo, M. A; Kawale, S.S; and Skinner, S. J; *Intermediate Temperature Solid Oxide Fuel Cells*, ed. Kaur, G. Elsevier, **2020,** 315–346, DOI: 10.1016/B978-0-12-817445-6.00010-7

86 Yatoo, M. A.; Du, Z.; Yang, Z.; Zhao, H.; Skinner, S. J. La$_x$Pr$_{4-x}$Ni$_3$O$_{10-\delta}$: Mixed A-Site Cation Higher-Order Ruddlesden-Popper Phase Materials as Intermediate-Temperature Solid Oxide Fuel Cell Cathodes. Crystals **2020,** 10, 428– 541, DOI: 10.3390/cryst10060428

87 Yatoo, M. A.; Du, Z.; Zhao, H.; Aguadero, A.; Skinner, S. J. La$_2$Pr$_2$Ni$_3$O$_{10\pm\delta}$ Ruddlesden-Popper phase as potential intermediate temperature-solid oxide fuel cell cathodes. *Solid State Ion.* **2018**, *320*, 148– 151, DOI: 10.1016/j.ssi.2018.02.043

88 Yatoo, M. A and Skinner, S. J, Ruddlesden-Popper phase materials for solid oxide fuel cell cathodes: a short review *Mater. Today Proc.* **2022** 56 3747–54, DOI: 10.1016/j.matpr.2021.12.537

89 W. Tinglian, L. Xiaofei, K. Chukun and W. Weppner, *Solid State Ion*, 1986, **18**, 715–719.

90 S. P. S. Badwal, *Solid State Ion*, 2001, **143**, 39–46.

91 A. M. Hernández, L. Mogni and A. Caneiro, *Int J Hydrogen Energy*, 2010, **35**, 6031–6036.

92 Z. Duan, M. Yang, A. Yan, Z. Hou, Y. Dong, Y. Chong, M. Cheng and W. Yang, *J Power Sources*, 2006, **160**, 57–64.

93 G. C. Kostogloudis, G. Tsiniarakis and C. Ftikos, *Solid State Ion*, 2000, **135**, 529–535.

94 J. A. M. van Roosmalen and E. H. P. Cordfunke, *Solid State Ion*, 1992, **52**, 303–312.

95 S. J. Skinner and J. A. Kilner, *Materials Today*, 2003, **6**, 30–37.

96 B. C. H. Steele, *Solid State Ion*, 2000, **129**, 95–110.

97 A. J. Jacobson, *Chemistry of Materials*, 2010, **22**, 660–674.

98 M. Han, X. Tang, H. Yin and S. Peng, *J Power Sources*, 2007, **165**, 757–763.

99 T. Ishihara, H. Matsuda and Y. Takita, *J Am Chem Soc*, 1994, **116**, 3801–3803.

100 P. Huang and A. Petric, *J Electrochem Soc*, 1996, **143**, 1644–1648.

101 N. Preux, A. Rolle and R. N. Vannier, *Functional Materials for Sustainable Energy Applications*, 2012, 370–401.

102 S. C. Singhal, *Solid State Ion*, 2000, **135**, 305–313.

103 S. Tao and J. T. S. Irvine, *Nat Mater*, 2003, **2**, 320–323.

104 W. Z. Zhu and S. C. Deevi, *Materials Science and Engineering: A*, 2003, **362**, 228–239.

105 J. Seo, J. Moon, K. Kim, N. Prasad Yerriboina, S. Sahir and S.-Y. Han, *Journal of The Electrochemical Society,* 1999, **146,** 1273-1278.

106    S. Tao and J. T. S. Irvine, *Chem Rec*, 2004, **4**, 83–95.