Introduction of solid oxide Fuel cell materials and components

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Abstract

Fuel cells offer the possibility of zero-emissions electricity generation and increased energy security. We review here the current status of solid oxide (SOFC) and polymer electrolyte membrane (PEMFC) fuel cells. Such solid electrolyte systems obviate the need to contain corrosive liquids and are thus preferred by many developers over alkali, phosphoric acid or molten carbonate fuel cells. Dramatic improvements in power densities have been achieved in both SOFC and PEMFC systems through reduction of the electrolyte thickness and architectural control of the composite electrodes. Current efforts are aimed at reducing SOFC costs by lowering operating temperatures to 500–800 ° C, and reducing PEMFC system complexity be developing 'water-free' membranes which can also be operated at temperatures slightly above 100 ° C.

Keywords: Fuel cells; Solid electrolytes; Electroceramics; Polymers; Platinum group metals.

1. Introduction

Because of their potential to reduce the environ-mental impact and geopolitical consequences of the use of fossil fuels, fuel cells have emerged as tanta-lizing alternatives to combustion engines. Like a combustion engine, a fuel cell uses some sort of chemical fuel as its energy source; but like a bat-tery, the chemical energy is directly converted to electrical energy, without an often messy and rela-tively inefficient combustion step. In addition to
high efficiency and low emissions, fuel cells are attractive for their modular and distributed nature, and zero noise pollution. They will also play an essential role in any future hydrogen fuel economy.

The primary components of a fuel cell are an ion conducting electrolyte, a cathode, and an anode, as shown schematically in Fig. 1. Together, these three are often referred to as the membrane-elec-trode assembly (MEA), or simply a single-cell fuel cell. In the simplest example, a fuel such as hydro-gen is brought into the anode compartment and an oxidant, typically oxygen, into the cathode com-partment. There is an overall chemical driving force for the oxygen and the hydrogen to react to produce water. Direct chemical combustion is pre-vented by the electrolyte that separates the fuel (H_2) from the oxidant
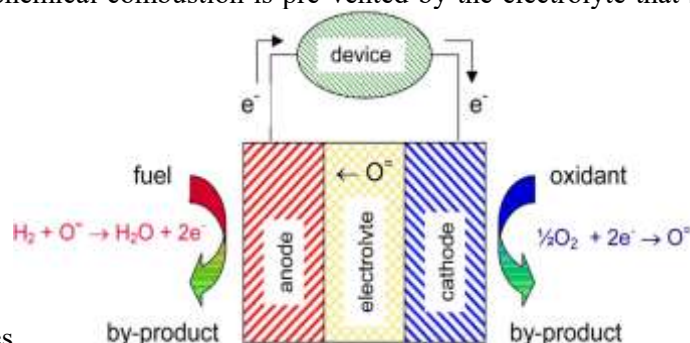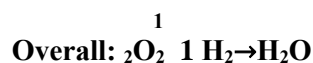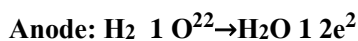

(O_2). The electrolyte serves

Fig. 1.   Schematic of a fuel cell, comprised of an electrolyte, an anode and a cathode. The overall chemical reaction is H_2 +   1/2 O_2

• H_2O. Anode and cathode reactions given are appropriate only for oxide ion conducting electrolytes. The reactions would be modifi ed for electrolytes with different mobile ions, but the general principle remains unchanged

•   as a barrier to gas diffusion, but will let ions migrate across it. Accordingly, half cell reactions occur at the anode and cathode, producing ions which can traverse the electrolyte. For example, if the electrolyte conducts oxide ions, oxygen will be electro-reduced at the cathode to produce $O^=$ ions and consume electrons, whereas oxide ions, after migrating across the electrolyte, will react at the cathode with hydrogen and release electrons:

Cathode: $\frac{1}{2}O_2 + 2e^2 \rightarrow O^{22}$

Anode: $H_2 + O^{22} \rightarrow H_2O + 2e^2$

Overall: $\frac{1}{2}O_2 + H_2 \rightarrow H_2O$

Analogous cathode and anode reactions for proton conducting electrolyte are:

Cathode: $\frac{1}{2}O_2 + 2H^+ + 2e^2 \rightarrow H_2O$

Anode: $H_2 \rightarrow 2H^+ + 2e^2$
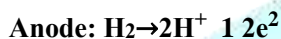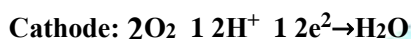
The fl ow of ionic charge through the electrolyte must be balanced by the flow of electronic charge through an outside circuit, and it is this balance that produces electrical power.

Electrolytes in which protons, hydronium ions, hydroxide ions, oxide ions, and carbonate ions are mobile are all known, and are the basis for the many categories of fuel cells under development today. Because ion conduction is a thermally acti-vated process and its magnitude varies dramati-cally from one material to the next, the type of electrolyte, which may be either liquid or solid, determines the temperature at which the fuel cell is operated. State-of-the art fuel cell electrolytes are listed in Table 1, along with the mobile ionic species, temperatures of operation and fuels typi-cally utilized. For reasons of electrode activity

Table 1				
Fuel cell types and selected features [1,2]				
Type	**Temperature ° C**	**Fuel**	**Electrolyte**	**Mobile ion**
PEM[a]: polymer electrolyte membrane	70– 110	H_2, CH_3OH	Sulfonated polymers (Nafion)	$(H_2O)_nH^+$
AFC: alkali fuel cell	100– 250	H_2	Aqueous KOH	OH^2
PAFC: phosphoric acid fuel cell	150– 250	H_2	H_3PO_4	H^+
MCFC: molten carbonate fuel cell	500– 700	hydrocarbons, CO	$(Na,K)_2CO_3$	CO_3^{22}
SOFC: solid oxide fuel cell	700– 1000	hydrocarbons, CO	$(Zr,Y)O_{2-d}$	O^{22}

Although substantial progress has been made over the last several decades in each of the fuel cell technologies listed in Table 1, only those employing solid electrolytes, PEMFCs and SOFCs.

In this review we present a brief discussion of the features that determine fuel cell performance,describe the state of the art in SOFC and PEM fuel cells, and evaluate electrolyte materials that may enable new types of fuel cells. Although electrodes/electrocatalysts are equally important to advanced fuel cells, space limitations preclude a meaningful overview of this topic. Readers are referred to an excellent overview of the many aspects of fuel cell science and technology by Car-rette and coworkers for additional information [3].

2. Fuel cell characteristics

The key performance measure of a fuel cell is the voltage output as a function of electrical current density drawn, or the polarization curve, Fig. 2 [4,5]. The measured voltage, E, can be written as
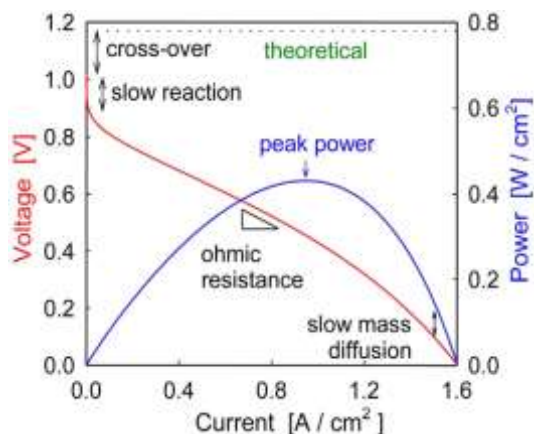

Fig. 2. Schematic fuel cell polarization (voltage vs. current density) and power density curves.

The power density is simply multiple of the voltage and the current density, and, as also shown in the fi gure, reaches some peak value at intermediate voltages (or current density). In contrast, efficiency, which decreases with increasing overpotential, is greatest at low current densities.

In the context of the polarization curve, it is evi-dent that high power densities (and high efficiencies) result when gas diffusion and electron transport through the electrolytes are slow, electro-catalysis at the electrodes is rapid, the conductivity of each of the components, in particular, the elec-trolyte, is high, and mass diffusion through the porous electrodes is facile. Thus, the ideal fuel cell *electrolyte* is not only highly ionically conducting, but also impermeable to gases, electronically resistive and chemically stable under a wide range of conditions. Moreover, the electrolyte must exhibit sufficient mechanical and chemical integrity so as not to develop cracks or pores either during manufacture or in the course of long-term operation. The demands on fuel cell electrodes are perhaps even more extreme than those on the electrolyte.

Additional components in a complete fuel-cell power generator are the so-called interconnects or bipolar plates. These components serve to link up individual fuel cells in a fuel cell stack; 'interconnect' is the term used in the SOFC community whereas 'bipolar plate' is that used in the PEM community. In addition to providing electrical conduction pathways, the interconnects/bipolar plates serve to keep oxidant and fuel gases separate from one another. Thus, the ideal interconnect has high electronic conductivity (its resistance contributes to the overall IR losses in the stack), excellent impermeability, and chemical stability under both oxidizing and reducing conditions. Good mechanical properties are also required, particularly for low temperature systems in which pressure is applied to maintain gas seals. For reasons of space limitations, these components will not be discussed in any detail. Sufficient it to note that tremendous efforts are being directed towards developing inex-
detrimental reactions occur over the many tens of thousands of hours expected for fuel cell lifetimes. Moreover, the components in high temperature fuel cells, must exhibit thermo-mechanical compatibility; that is, the thermal expansion coefficients must match, and/or the materials must be tough enough to withstand mechanical stresses due to differences in thermal expansion.

3. Solid oxide fuel cells: State-of-the-art

An excellent review of ceramic fuel cells and the materials from which they are constructed has been presented by Minh [9], and we only briefly summarize here the technology status for what one can term 'conventional' solid oxide fuel cells. Somewhat more recent, but less comprehensive, reviews have been published by Ormerod [10] and by Singhal [11]. Today's demonstration SOFCs utilize yttria stabilized zirconia (YSZ), containing typically 8 mol% Y, as the electrolyte; a ceramic-metal composite (cermet) comprised of Ni + YSZ as the anode; and $La_{12x}Sr_xMnO_{3-d}$, (lanthanum strontium manganite or LSM) as the cathode. Specific anode and cathode compositions are often omitted from publications, but typically x is 0.15 to 0.25 in LSM cathodes, whereas Ni-YSZ anodes are prepared from ~50:50 wt ratio NiO + YSZ mix-tures which are subsequently reduced in situ to yield Ni metal particles dispersed in a porous YSZ matrix. Anode and cathode porosities are typically 25– 40 vol%. The interconnect material is alkali doped $LaCrO_3$ (lanthanum chromite), with the spe-cific dopant (typically, Sr, Ca or Mg) and concentration being selected to best match the thermal expansion of the other fuel cell components in the geometry of interest. In addition to these four components, planar SOFCs require sealant materials to isolate anode and cathode chambers in a stacked confi guration. The literature on SOFC sealants is limited, but these have been typically fabricated from various glasses or glass-ceramics. Recent advances in YSZ-based fuel cells include a move from electrolyte or cathode supported structures to ones in which the anode serves to sup-port a thin electrolyte and thin cathode, and the use of composite, YSZ + LSM,

cathodes (YSZ:LSM =50:50) rather than simply LSM. These design changes, together with improved fabrication tech-niques, have resulted in an increase in peak power densities for laboratory planar cells operated on hydrogen from ~250 mW/cm^2 @ 1000 ° C
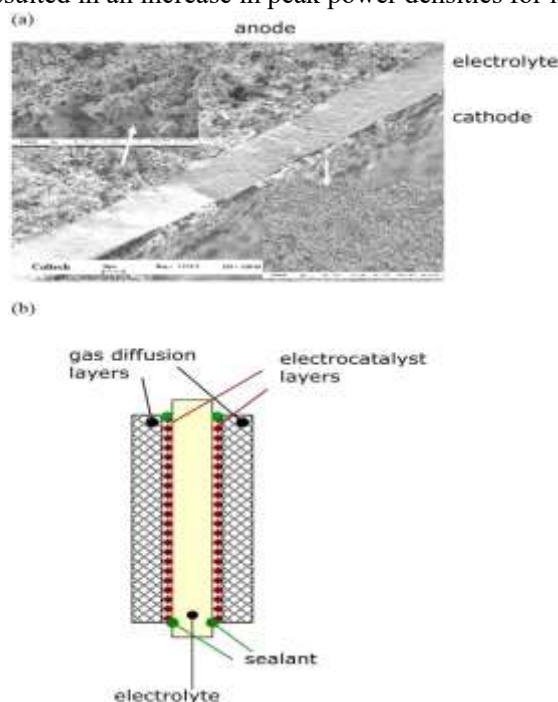
Fig. 3. Membrane-electrode-assemblies: (a) scanning electron micrograph of a typical SOFC structure obtained in the author's laboratory; (b) schematic of a PEM structure in which gas dif-fusion layers, are additionally incorporated. Together, the elec-trocatalyst and gas diffusion layers are often referred to as the gas diffusion electrodes.

- ## Polymer electrolyte membrane fuel cells: State-of-the-art

Polymer electrolyte membrane (PEM) fuel cells have been reviewed by Costamagna and Srinivasan [17, 18] and readers are referred to that work for a more comprehensive discussion than can be pro-vided here. The most widely implemented electro-lyte in PEM fuel cells is Nafion manufactured by DuPont. Nafi on and related polymers are comprised of perfluorinated back-bones, which provide chemical stability, and of sulfonated side-groups which aggregate and facilitate hydration (see dis-cussion below). It is these hydrated, acidic regions which allow relatively facile transport of protons, but also restrict PEMFCs to low temperatures of operation. As a consequence, precious metals are required for electrocatalysis. For hydrogen/air fuel cells, Pt nano-particles supported on carbon are uti-lized for both the anode and cathode. Proprietary Pt-based alloys may instead be used in the anode of fuel cells using 'impure' hydrogen, that is, hydrogen obtained by steam reforming of hydro-carbon fuels. The reformate from such processes can contain 10 s to 100 s of ppm CO and this has detrimental impact on fuel cell performance as a result of the strong adsorption of CO onto Pt. In direct methanol fuel cells PtRu alloys (typically 50:50 molar ratio) are used at the anode because of the ability of Ru to electrooxidize CO adsorbed onto Pt. The platinum content (or Pt loading) in

hydrogen/air PEM fuel cells has been reduced dra-matically over the past decade from ~4 mg/cm^2 (per electrode) to less than 0.4 mg/cm^2, as a result of optimal dispersion of nanoparticle Pt in the elec-trocatalyst layer of the fuel cell. In contrast to SOFCs, the current collector, which also serves as a gas diffusion layer, is a distinct but integral component of the PEM membrane-electrode-assembly. Typically, highly porous carbon paper treated with a hydrophobic polymer (e.g. PTFE) is used. In the fabrication of a stack, graphite bipolar plates are placed between individual MEAs. Recent advances in perfl uorosulfonated polymer based fuel cells include reduction of the electrolyte thickness from ~175 to ~ 25 $\square$ m, an increase in the extent of sulfonation of the polymer to increase conductivity, control of the porosity in the electro-catalyst and gas diffusion layers, and optimization of the MEA processing to achieve excellent adhesion between the multiple layers. These devel-opment efforts have led to increases in the power densities of hydrogen/air PEM fuel cells from ~100 mW/cm^2 in 1984 to over 1 W/cm^2 in 2002 [1].

The long-term durability of PEM fuel cells is more of a concern than that of continuously operated SOFCs, although Ballard has reported 2000 h of operation without measurable loss in PEMFC power output. More signifi cant at this stage than long-term durability is the hydration requirement of the polymer in order to maintain conductivity. First, because, in fact, hydronium ions, $(H_2O)_nH^\square$, rather than bare protons are transported across the membrane, excess water must be removed from the cathode and replenished at the anode. Second, upon hydration, sulfonated polymers swell signifi - cantly and their mechanical properties can degrade. Third, operation is generally limited to ,~ 90 $\square$ C, at which temperatures the precious metal anode catalysts are susceptible to CO poisoning, and electrocatalysis at both electrodes is generally sluggish. Higher

temperatures of operation open up the possibility of simplifying the CO removal process, lowering Pt loadings and even the use of non-pre-cious metal catalysts. And fourth, as a consequence of its miscibility with water, methanol easily dif-fuses across the hydrated polymer electrolyte from the anode to the cathode (fuel cross-over) resulting in signifi cant effi ciency losses and low power den- sities. Indeed, to minimize cross-over, relatively thick membranes (~175 □ m) and low methanol concentrations (~4% in H_2O) are used in direct methanol fuel cells [19]. Despite the drawbacks associated with perfluorinated sulfonated polymers, Nafi on and its close relatives continue to be the electrolyte of choice in demonstration PEMFCs because of their combination of very high conductivity and adequate mechanical properties.

5. Electrolytes

The most important property of a candidate electrolyte material is, of course, the ionic conduc-tivity. Conductivity data of a broad range of materials are summarized in Fig. 4 [20– 25]. Material classes for electrolyte applications range from ceramics, to polymers to acid salts, and the mobile ion can be O^{22}, $H^{□}$, or $(H_2O)_nH^{□}$. Solids for which OH^2 or CO^{32} are mobile are also known, but the conductivities are not high enough to be of technological relevance. It should be noted that independent of the magnitude of the conduc-tivity, fuel cell design inherently leads to a preference for a specific mobile species. In general, hydronium, hydroxide and carbonate ion conductors are unattractive because one must, by defination, recycle an otherwise inert species: H_2O in the case of hydronium and hydroxide conductors or CO_2 in the case of carbonate conductors, to maintain ion transport.

Where hydrogen is the fuel, a proton conductor offers the benefits of generating the by-product H_2O at the cathode, and thus the fuel does not become diluted as a function of utilization. Consequently, so long as oxygen is plentiful, cell voltages remain high. Hydronium ion conductors generally provide this same benefit, however the water recirculation requirements noted above

demand delicate water management. In the case where hydrocarbons serve as the fuel, an oxygen ion conductor offers, in principle, the prospect of direct electro-oxidation:

$$CH_4 \; 1 \; 4O^{22} \rightarrow CO_2 \; 1 \; 2H_2O \; 1 \; 8e \; 2$$

Fig. 4. Conductivities of selected electrolyte materials. (a) High temperature conductors [20– 22]; and (b) low temperature conductors [23– 25]. PBI is polybenzymidazole where high and low refer to the acid content; PWA is phosphotungstic acid and the numeral following the acronym is the number of water molecules of hydration.
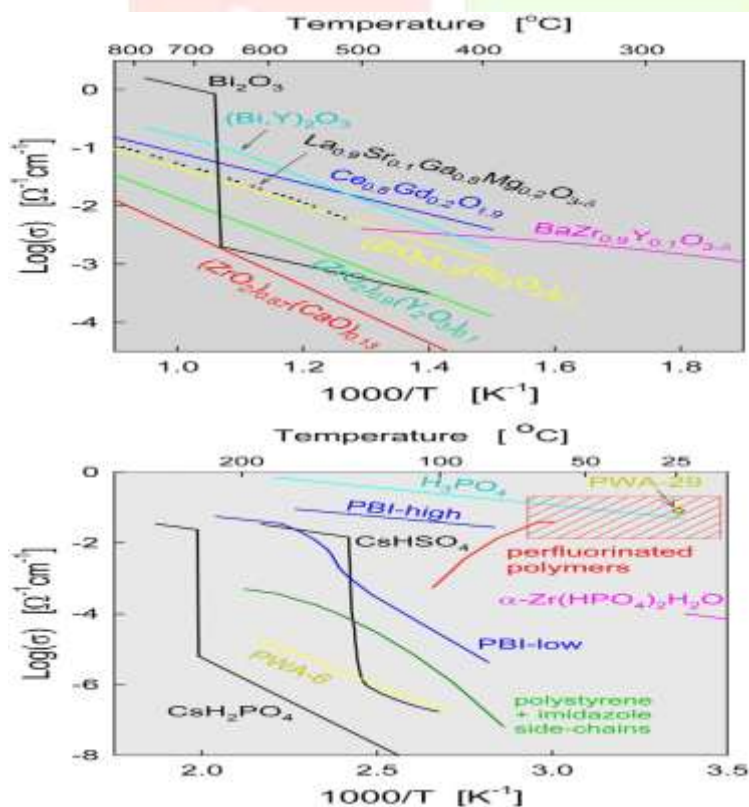

Instead presumed that the high temperature of operation associated with oxygen ion conductors can be used to facilitate internal steam reforming:

$$CH_4 \; 1 \; H_2O \rightarrow CO \; 1 \; 3H_2 \qquad (14)$$
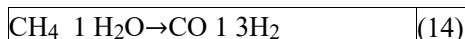
with CO and H_2 then used in the electro-oxidation reactions. Even in this more conservative scenario, oxygen-ion conducting electrolytes are preferred because CO can be electro-oxidized, rather than (particularly in the case of low temperature

systems) poisoning the anode catalyst. Ceramic proton conductors may offer an interesting combination of benefits because of their ability to transport both protons and oxygen ions. It has been suggested [26] that water can diffuse across the electrolyte membrane, inducing steam reforming and even conversion of CO to CO_2 through the water-gas shift reaction:

$$CO \; 1 \; H_2O \; \rightarrow CO_2 \; 1 \; H_2. \qquad\qquad (15)$$
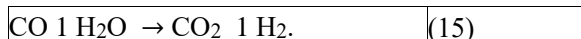
Hydrogen generated by reactions (14) and (15) is then electrooxidized to form protons. In this case, hydrocarbons can be directly utilized and no water is produced at the anode, again avoiding dilution effects as fuel utilization increases (although CO_2 dilution still occurs).

5.1. Oxygen ion conductors

The classic oxygen ion conductors, stabilized (cubic) zirconia and ceria are based on the fl uorite structure, Fig. 5. In order to introduce mobile oxy-gen vacancies into the compound, and, in the case of zirconia, stabilize the cubic structure, tri- or divalent dopants are added to the host material. The incorporation reaction can, for a typical tri-valent dopant.

with one oxygen vacancy created for every two M atoms incorporated. For both zirconia and ceria, conductivity increases with increasing dopant concentration up to some maximum value and then decreases sharply. Similarly, the conductivity increases then decreases across the rare earth series from Yb to La. For zirconia, Sc gives rise to the highest conductivity, but Y is typically utilized for reasons of cost. With yttrium as the dopant, the conductivity of zirconia peaks at about 8 mole % dopant concentration. In the case of ceria, Sm [27] and Gd [28] give the highest values of conduc-tivity, and optimal dopant concentrations are 10– 20%. The strong dependence of ionic conduc-tivity on dopant type and concentration has been explained in terms of the lattice distortions introduced by the dopant, with those that produce the least amount of strain causing the smallest variation in the potential energy landscape [29]. Over-all, the ionic conductivity of ceria is approximately an order of magnitude greater than that of stabilized zirconia for comparable doping conditions. This is a result of the larger ionic radius of Ce^{4+}

which produces a more open structure through which $O^=$ ions can easily migrate.

Despite its favorable ion transport properties, ceria had not, until quite recently, been considered a realistic candidate for fuel cell applications because of its high electronic conductivity. In particular, under reducing conditions, CeO_2 becomes CeO_{22x}, and n-type conductivity increases with a $P(O_2)^{21/4}$ dependence. From an analysis of relevant literature data, Steele [28] has proposed that the electrolytic domain boundary, the oxygen partial pressure at which electronic and ionic conductivities are equal, can be estimated as shown in Fig. 6(a), for 10 and 20% Gd doped ceria. In principle, one expects to be well within the electrolytic domain of ceria for fuel cells operated below 700 ° C, although even at these temperatures some voltage loss is expected. Reported open circuit potentials for doped ceria, Fig. 6(b), are lower than what one would expect on the basis of the electronic conductivity of ceria and represented simply as the multiple of the ionic transference number (greater than ~0.9 [30] at 700 ° C and 10^{218} atm oxygen partial pressure) and the Nernst potential. The reasons for this discrepancy are not entirely obvious, but are likely due to electrode (in particular cathode) overpotentials, and emphasize the importance of developing electrodes compat-ible with ceria that enable theoretical open circuit potentials to be reached. An additional challenge lies with the chemical expansion of ceria under reducing conditions and the internal stress that result [31]. At this stage, the signifi cance of this issue on the long-term viability of ceria-based fuel cells is unknown. It is noteworthy that planar cells experience lower stresses than tubular cells, sug-gesting that clever designs may alleviate possible stresses.
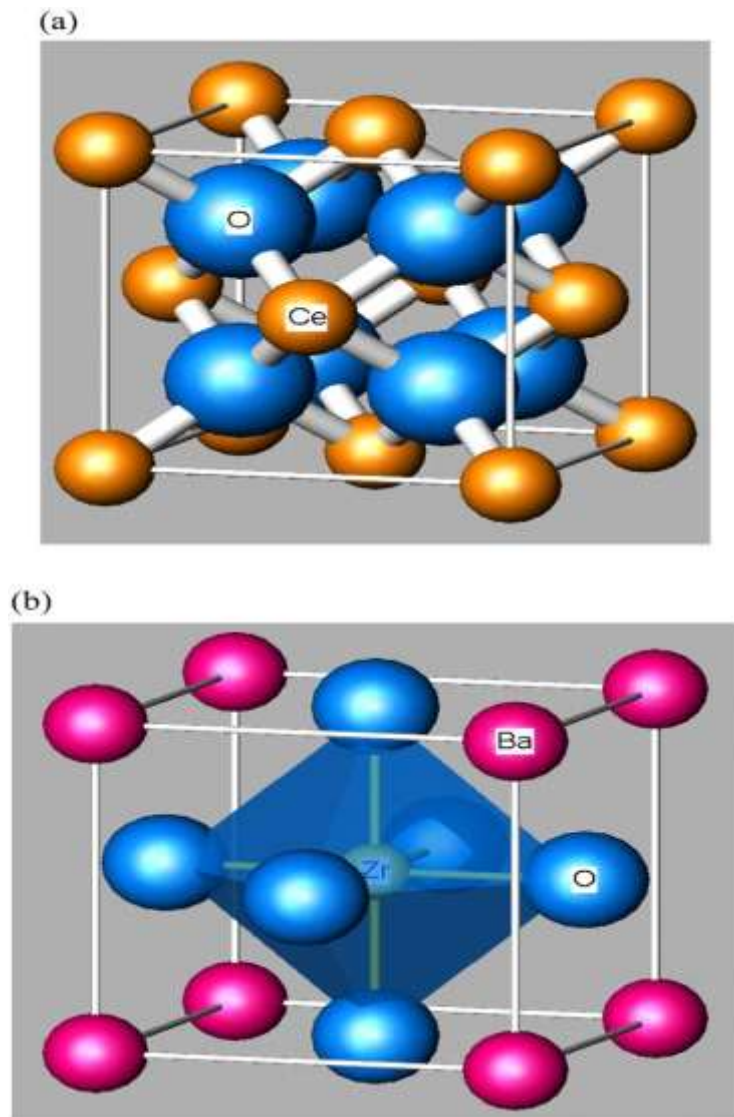
Fig. 5. Crystal structure of conducting oxides: (a) fluorite structure, exhibited by stabilized zirconia and by ceria; (b) per-ovskite structure, exhibited by oxygen ion conducting LaGaO₃, and by proton conducting BaZrO₃.

Fig. 6. Electrochemical properties of doped ceria [43]: (a) Electrolytic domain boundary at which ionic conductivity equals electronic conductivity, after [28]; (b) Open circuit potential for a hydrogen (3% H₂O) // oxygen cell. The Nernst potential is that expected for an ideal electrolyte, the dotted line is approximately that expected for an electrolyte with 10% electronic conductivity and the red and blue curves are experimental data.

Oxide-ion conducting perovskites have appeared in the literature for several years, but only recently have compositions with conductivities high enough for consideration in fuel cell applications appeared. The ABO_3 perovskite structure, Fig. 5, is extremely amenable to tailoring via doping on both the A and B cation sites. A large variety and concentration of dopants can be accommodated in a wide range of host compounds. Introduction of divalent dopant ions, typically Sr and Mg, onto the La and Ga sites, respectively, of lanthanum gallate produces a material with a high concentration of mobile oxygen vacancies and thereby high oxygen ion conductivity. The conductivity of the particular
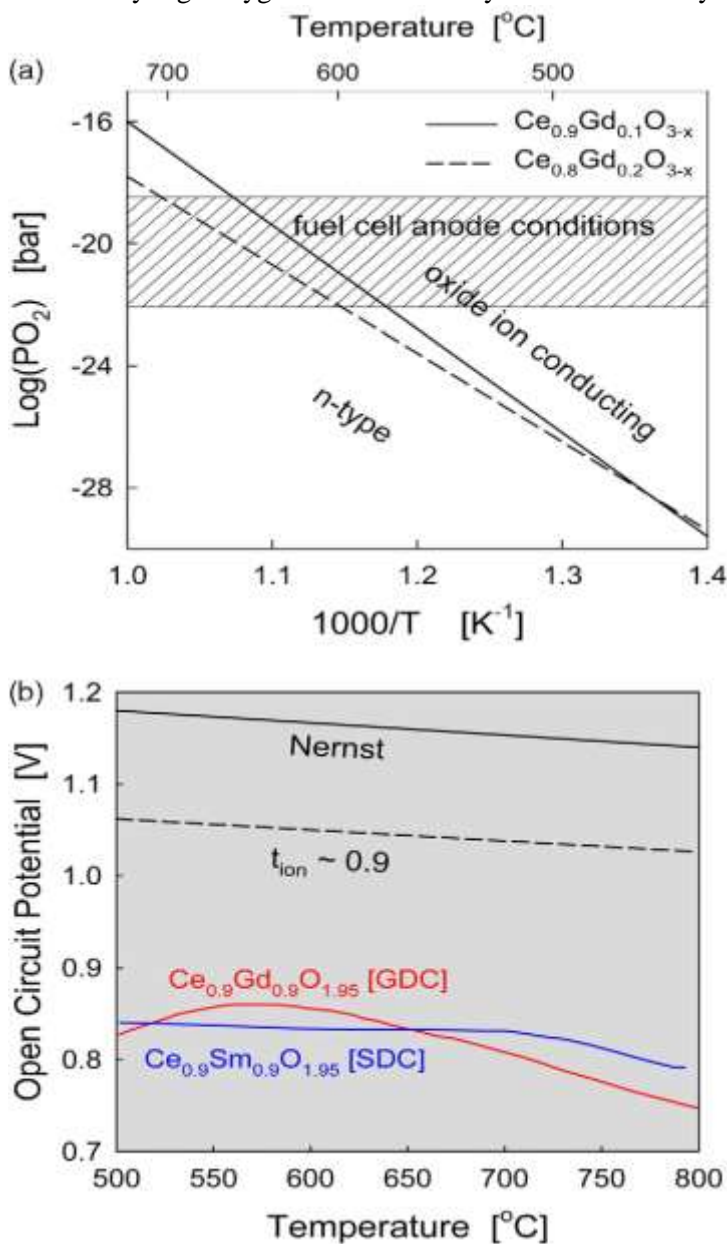
Composition $La_{0.9}Sr_{0.1}Ga_{0.8}Mg_{0.2}O_{32d}$ was reported almost simultaneously by Goodenough and

Coworkers [32] and by Ishihara and coworkers [21]. The transport properties of LSGM, as it is known, are comparable to those of scandia-doped zirconia. The conductivity is entirely ionic over an extremely wide oxygen partial pressure range at temperatures as high as 1000 □ C, but is not as high as that of suitably doped ceria. Thus, the conditions under which LSGM might be preferable to doped ceria appear limited to the temperature range of 700– 1000 □ C. Moreover, lanthanum gallate suffers from reactivity with nickel, the typical SOFC anode electrocatalyst. To address this challenge, (non-reactive) ceria buffer layers have been incor-porated between the electrolyte and the anode [33]. Nevertheless, intensive research efforts to develop SOFCs incorporating lanthanum gallate continue, and recent work suggests that the ionic conduc-tivity can be increased by further adjustments to the stoichiometry, in particular, via the addition of small concentrations of Ni or Co [34]. A sampling of recent achievements in fuel cell research using ceria and LSGM electrolytes is summarized in Table 2.

The ion transport properties of bismuth oxide have received significant academic attention as a result of a rather spectacular phase transition at ~700 □ C which leads to an increase in conductivity by almost three orders of magnitude. In the high temperature d phase, the compound has a cubic.

Fig. 7. Structure of perfluorinated sulfonated polymers (i.e. Nafi on and its close relatives). (a) Chemical structure; (b) nanoscale phase separated microstructure as determined by SAXS (small angle X-ray scattering), after [49]; (c) microstructure as predicted by molecular dynamics simulations,
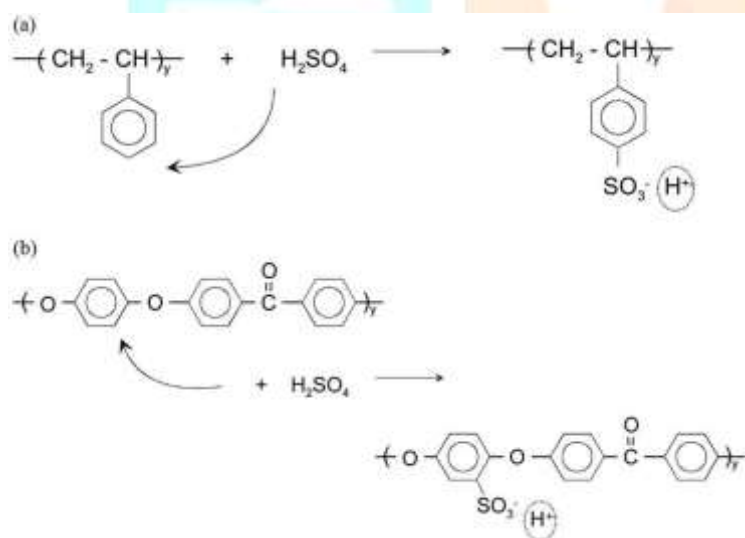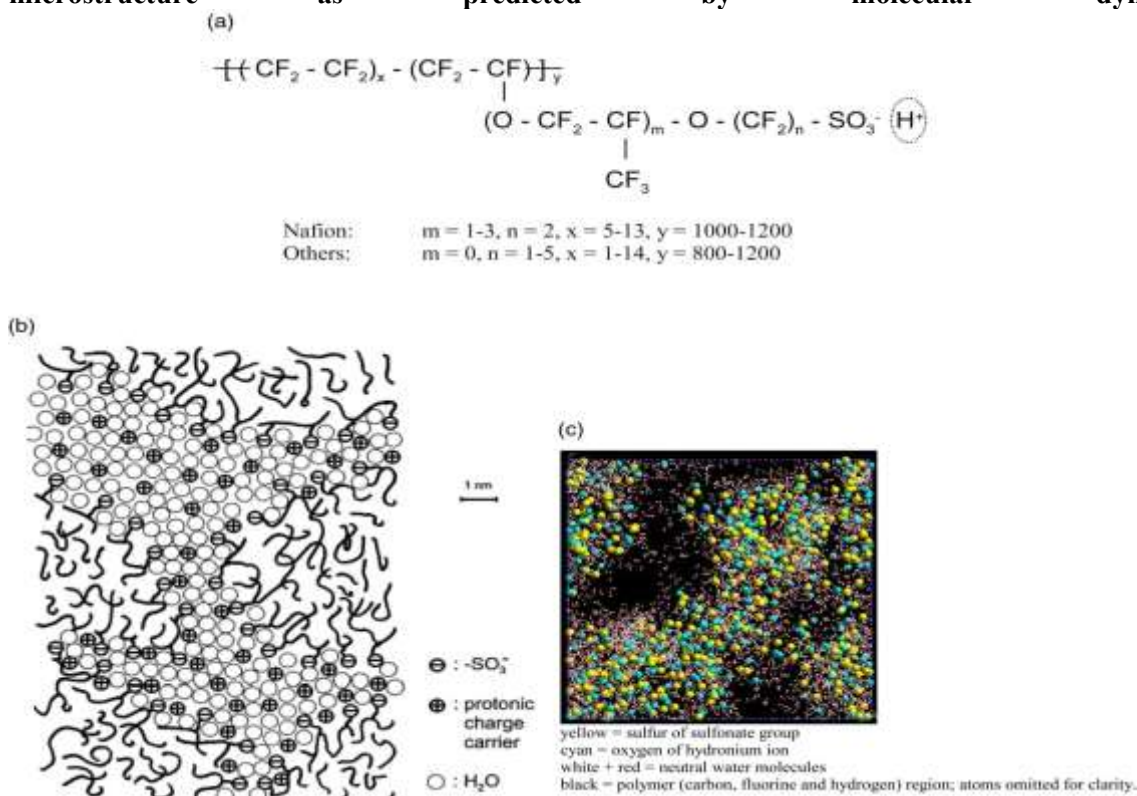

Fig. 8. Chemical structures of (a) polystyrene and its sulfonated analog, poly (styrene sulfonic acid) [PSSA] and (b) polyether ether ketone and its sulfonated analog, S-PEEK. The most likely site for sulfonation of the polymer host is indicated

Another route for eliminating water from proton conductors is to return to sulfonated polymers, but replace the water with a less volatile ionic liquid, in particular heterocyclic amines such as imidazole (pyrazole) and benzimidazole [58]. The nitrogen sites in these compounds can act as proton acceptors with the acidic sulfonic groups of the host polymer serving as proton donors. Proton conductivities as high as 10^{22} S/cm at 200 □ C have been reported for a sulfonated aromatic polymer. host intercalated with ~7 imidazole molecules per sulfonic group. A further modification to this approach is to link the imidazole groups directly to the polymer back-bone in order to prevent loss of the ionic liquid. Appropriate tethering ensures that the heterocyclic groups can aggregate and pro-ton transport properties are ideally retained. Although materials with conductivities comparable to those of conventional sulfonated perfluorinated polymers have not yet been developed, Fig. 4(b), the flexibility of the approach provides many avenues for continued investigations. Care must be taken, however, that gains in eliminating water from the polymer electrolyte do not come at the expense of electrode performance, which may continue to require a hydrated polymer as part of the electrocatalyst layer so as to ensure access of fuel and oxygen to the polymer-coated catalyst particles.

Fig. 9. Proton transport mechanism in a disordered acid sulfate compound. HSO_4^2 tetrahedra undergo rapid reorientations with the proton attached to a particular oxygen atom, left; proton transfer from one tetrahedron to the next occurs on a much slower time scale, right.
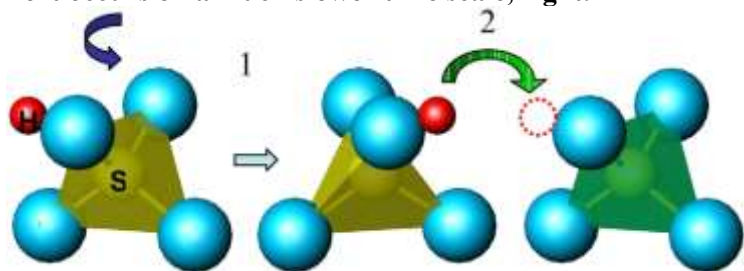
Fig. 10. Schematic of a single chamber fuel cell. A hydro-carbon fuel is partially oxidized at the anode producing CO and H_2 and consuming O_2. The resulting oxygen partial pressure gradient drives the electrochemical reactions of the fuel cell.

Complications due to sealing are eliminated; the SOFC greatly simplifies system design and enhances thermal and mechanical shock resistance, thereby allowing rapid start up and cool down. While it may seem optimistic, at first glance, to expect that catalysts could be sufficiently selective so as to yield good power densities, such chemical precision is routinely utilized in nature. Indeed, biofuel cells operating on aqueous glucose, that is not separated from ambient oxygen, demonstrate essentially perfect electrode selectivity [73] and may ultimately enable extremely compact fuel cell designs that are ideally suited to miniature, low-power applications.

7. Conclusions

After almost a century of slow and at times almost sputtering progress, fuel cell research has exploded with activity over the past decade. The results have been tremendous, with power densities increasing by factors of two and catalyst utilization by more than an order of magnitude. These achievements have resulted from the development of new materials (e.g. $La_{12x}Sr_xGa_{12y}Mg_yO_{32d}$ oxide ion conductors) as well as new processing techniques (e.g. electrocatalyst-layer deposition for polymer electrolyte fuel cells). Reduction of cost and system complexity remain signifi cant chal-lenges. Current efforts in SOFC research are aimed at (1) reducing operating temperatures to 500– 800 C to permit the use of low-cost ferritic alloys for the interconnect component of the fuel cell stack and (2) enabling the direct utilization of hydro-carbon fuels. Achieving these goals will require the development of highly active cathode materials and of highly selective anode materials that do not catalyze carbon deposition. Ceramic electrolytes that are operable at reduced temperatures are avail-able (doped ceria and LSGM) but high performance single-cell fuel cells based on these materials have yet to be demonstrated. Current efforts in PEMFC research are focused on (1) reducing membrane cost via the use of non-fluorinated polymer electrolytes and (2) reducing system com-plexity via the development of 'water-free' electroytes that do not require cumbersome hydration paraphernalia. Such electrolytes would additionally. Enable operation under 'warm' conditions (i.e. above 100 ° C) and be impermeable to methanol. Additional PEMFC research is very much directed towards the development of high activity cathode electrocatalysts and CO tolerant anode electrocat-atlysts, which would furthermore be well-suited to direct methanol fuel cells. Dramatic reductions in the content in PEM fuel cells have been achieved over the past 20 years; however complete elimination of remains a goal. Successes in these arenas of cost and complexity reduction rely on continued advances in materials development and fabrication routes, and are essential for realizing the market and environmental potential of fuel cells.

Acknowledgements

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