Perspective

Nano-scale view into solid oxide fuel cell and semiconductor membrane fuel cell: material and technology

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**Abstract**

Fuel cells could play an important role in the energy transition ahead by providing clean and efficient energy conversion. Solid oxide fuel cell (SOFC) technology is a potential alternative for large-scale application, but its commercialization limited by the electrolyte material has not yet been realized. Progresses on the new functional semiconductor-ionic materials (SIMs) and on the fundamentals of SOFC may provide new paths for its research and development (R&D). Herein, we discuss the nano-scale electrochemistry phenomena of SIMs to bring new concepts for advanced SOFCs. A traditional SOFC consists of a three-layer anode/electrolyte/cathode structure, where the physically separated electrolyte layer is indispensable for ion transport to support the redox reaction and preventing occurrence of shorting circuit problem. A novel nano-SOFC concept is proposed to replace the traditional electrolyte by a SIM or semiconductor membrane (SM), and it can deliver superior performances even at a lower temperature range (< 500 °C). The scientific bases and prospects of this new technology approach are viewed and discussed.

**Keywords:** Semiconductor-ionic materials, nano-fuel cell, semiconductor membrane fuel cell, triple-charge conduction
1. INTRODUCTION

Climate change mitigation will require massive introduction of clean and efficient energy production in the coming decades. The Paris Climate Accord from December 2015 calls for limiting the global temperature rise to 1.5 °C, which means reaching carbon neutrality around the middle of this century. Many countries such as China, the EU and the USA have committed to these goals.

In the circumstances, global energy transition requires a multitude of new technologies to be developed for utilizing existing fossil fuels in a clean and more environmental benign way, as well as exploiting renewable energies. Fuel cells which convert fuels to electricity with high efficiency through the electrochemical route is one of promising technologies, possibly more appropriate for hydrogen era over battery technology. Solid oxide fuel cell (SOFC) delivers the highest efficiency when converting chemical energy to electricity among other types of fuel cells, but its wider use is still hampered by degradation and material reliability issues due to relatively high operating temperatures (800 °C~1000 °C). Lowering the temperature below 600 °C has therefore been an important goal for recent SOFC research. As pointed out by Goodenough, SOFC commercialization would need an oxide-ion conductor with sufficient conductivity at a lower temperature range to be technically and commercially useful [1]. In order to reduce the operating temperature of SOFC, some earlier research and development (R&D) activities had been focused on thin-film fabrication technologies to reduce the thickness of the electrolyte layer to obtain better electrochemical performance at ca. 700 °C [2, 3]. An alternative path considered was to replace the most commonly used yttria-stabilized zirconia (YSZ) with a better ionic conducting electrolyte at low operating temperatures. In addition, new scientific understanding of the charge transfer mechanisms at nano-scale occurring at a new set of alternative materials, such as mixed semiconductor-ionic materials, is being considered to open up radically new opportunities for SOFC at even lower temperature, e.g. below 550 °C.

The SOFC is composed of a dense electrolyte layer assembled between two porous electrodes (anode and cathode) [4]. The basic working principle of the SOFC is based on oxygen ion (O^{2-}) conduction by oxygen reduced at the cathode. The oxygen ions
are transported through the electrolyte layer, e.g. YSZ, which also acts as a separator to prevent a direct reaction between the fuel and oxidant. The free electrons created in the electrochemical oxidation of the fuels at the anode side travel through an external circuit to generate electric power (Figure 1a). Using protons (H\(^+\)) as the charge carrier instead of oxygen ions has also been well investigated, which converts the SOFC into proton ceramic fuel cells (PCFCs) [5, 6]. In this case, hydrogen is oxidized at the anode to generate protons, which are transported through the dense electrolyte layer to react with O\(_2\) at the cathode side to complete the redox reaction for electric power generation (Figure 1b). Compared to the SOFC, the PCFC can operate at lower temperatures as proton diffusion requires lower activation energy to motivate, typically generating power densities up to 0.455 W cm\(^{-2}\) at 500 °C [6].

![Figure 1. Schematic diagram of (a) oxygen ion and (b) proton conduction in SOFC.](image)

2. **State-of-the-art and challenges of traditional SOFC**

Commercial-scale SOFC systems generating hundreds of kilowatts (kW) were already built at the end of the 1990s [7, 8]. These included tubular SOFC stacks (Figure 2a) which were used in the Siemens/Westinghouse 220 kW SOFC power station, and a 3 MW power plant was planned. The tubular SOFCs used thick YSZ (around 200 μm) electrolyte tubes and have been successfully operated at 900-1000 °C. However, it was not cost-effective due to the high operating temperature. Planar cells and stacks development by Bloom Energy (Figure 2b), General Electric, Siemens, Ceres Power (Figure 2c), etc. advanced in reducing the YSZ electrolyte thickness down to several micron-meters using mature and scalable
thin film manufacturing techniques, such as screen printing or tape casting without compromising its mechanical strength (e.g. with external stainless steel support). Such thin-film YSZ electrolyte showed promising results at intermediate- and low-temperature operation (500-750 °C) [9, 10]. Bloom Energy, which is deemed as the most successful commercial SOFC manufacturer, has provided SOFC products in various system formats, e.g. micro-grid/energy server/power stations (https://www.bloomenergy.com/). The SOFC produced by Bloom used mixtures of scandia-stabilized zirconia (ScSZ) and YSZ based on flat-sheet design, running on hydrogen, natural gas and even biogas. However, deploying these products was restricted to on-site or stationary power generation only, mainly due to the high working temperatures. Besides, the UK-based Ceres Power featured a unique metal-supported cell design using porous stainless-steel substrates as thick films (200–300 μm) with laser-drilled gas channels. The cell components were subsequently deposited as thin-films of 10-15 μm. It is noteworthy that the composite electrolyte based on gadolinium doped ceria (GDC) has a sandwich structure with a buffer layer in the middle, as depicted in Figure 2c [11], realizing stable low-temperature operation at 500 °C. This design enabled the construction of fuel cell stacks/systems in tens of kilowatts for flexible applications such as domestic combined heat and power (CHP) system, auxiliary power units (APU), and recently for the fast-growing electric bus markets [12]. Meanwhile, SOFCMAN which uses planar SOFCs has recently demonstrated a 25 kW SOFC system, showing a peak power of 30.3 kW with 60.8% electrical efficiency and 79.8% fuel utilization rate (http://www.sofc.com.cn/2021011401.asp).
Figure 2. (a): Tubular SOFC cells and a system delivering 220 kW, Siemens/Westinghouse [7,8]; (b): Bloom energy SOFC products from a single cell, stack to power systems; (c): Cross-sectional image of a metal supported SOFC cell from Ceres Power Ltd. and exemplary single cell from Ceres Power. (Copyright from ECS Trans. 2017; 78: 87.)

Facing the commercialization challenges of macro-power plants, micro-tubular and micro-plate SOFC designs have been developed in parallel for portable and mobile applications due to high thermal stability during rapid heat cycling and large volumetric active surface area. These include 50-100W micro-tubular SOFC stacks from the Japanese New Energy and Industrial Technology Development Organization (NEDO) (0.8–1.6 mm tube diameter) with electrolyte thickness < 5 μm leading to improved power densities at reduced temperature (0.5 W cm$^{-2}$ at 550 °C) [13]. Japan's Institute of Industrial Technology has further developed a ‘mini’ stack working at 550 °C based on needle-type SOFC single cells, in which the diameter is reduced to
sub-millimeter scale (ca. 0.8 mm) so to increase the volumetric active electrode area. The micro-SOFC cell is capable of rapid start-up and may benefit of cost reduction through high volumetric power density, which is crucial for portable applications.

The electrolyte thickness could further be reduced through advanced vacuum deposition techniques such as atomic layer deposition (ALD) [14,15], inkjet printing [16], pulsed laser deposition (PLD) [17], and chemical vapor deposition (CVD) [18], yielding YSZ electrolyte thicknesses in the range from 50 to a few hundred nanometers so the cell could generate power density up to 90 mW cm\(^{-2}\) at 400 °C [17]. Some adverse effects by utilizing thinner films have been identified, including mechanical failures due to intrinsic stress from the YSZ membrane growth mechanism and the extrinsic stress induced by the thermal expansion coefficient (TEC) mismatch, which then deteriorates the long-term stability of micro-SOFC. All in all, limited by the poor conductivity of YSZ electrolyte at the given temperature range, enabling sufficient ionic conduction in electrolyte still remains as one of the critical objectives towards SOFC commercialization.

3. **Novel-SOFC concept**

Recent developments in nanomaterials have played a crucial role in improving the electrocatalytic properties of redox reactions and correspondingly electrochemical performances. However, the performance of SOFC is affected by multiple factors including the intrinsic properties of the basic components (anode, electrolyte, cathode) and the polarization losses at electrolyte/electrode interface. In the traditional SOFC, anode/electrolyte and cathode/electrolyte interfaces considerably affect the device performance leading to severe polarization losses. In this case, two functional layers, also known as active layers which are composed of a delicate mixture of electrode and electrolyte materials with fine structure, have been introduced for dealing with this problem. The newly developed novel SOFC has distinguishable feature from the conventional counterpart that has the electrolyte-separated electrode interfaces, and HOR (hydrogen oxidation reaction) and ORR (oxygen reduction reaction) respectively in the anode and cathode as illustrated in Figure 3a and Figure 4a. While the new type device does not have a physically separated electrolyte layer, it is constructed using a semiconductor membrane (SM) or SIM to realize the fuel cell HOR and ORR in a single-layer design, as shown in Figure 3b, through a nano-redox
mechanism [19, 20]. The SM/SIM can be a mixture of the SOFC’s oxide cathode material with p-semiconducting property and an ionic electrolyte [21-23], whose composition is similar to a cathode component used in SOFC [24, 25]. In this way, the interfacial polarization losses can be removed, and the nano-scale redox phenomena of a complete fuel cell reaction can be scaled up into a single layer device to form a macro-scale generator that can function in the way as the conventional SOFCs, as illustrated in Figure 3b.

Figure 3. (a): The SOFC device with a three-layer anode/electrolyte/cathode structure. (b): Nano-SOFC with a single-layer SIM structure.

4. Nano-SOFC fundamentals and working principles beyond macro-scales

Singh and Nowotny [26] proposed a new understanding on the SOFC that the anode, electrolyte, and cathode of a fuel cell can be interpreted as n-type, ionic and p-type layers/zones, respectively, as shown in Figure 4a, where the electrolyte layer separates HOR and ORR. If the middle electrolyte layer is removed (ionic zone), it is converted into a two-component (layer) device with n (anode) and p (cathode)-type conduction, which is also known as a p-n junction device (Figure 4b). By this means, electronic short-circuiting risk can be prevented due to the charge separation function of the p-n junction, just like the principle of a p-n solar cell. This suggests that a physically separated electrolyte layer may not actually be an indispensable component to run a SOFC. In fact, the feasibility of such double-layer fuel cell constructed by the anode and cathode only had been demonstrated earlier [27]. Moreover, the anode, electrolyte, and cathode can be further integrated at nano-scale through nano-particles consisting of n-type, ionic and p-type elements, which is known as nano-redox unit as illustrated in Figure 4c, thus a fuel cell redox reaction as discussed above can be realized at
nano-particle scale, this suggests that a nano-SOFC could be constructed. The single-layer fuel cell is an up-scale device for the nano-redox or nano-SOFC units (Figure 4c). These units form a bulk p-n heterostructure junction in a energy band alignment, so that the generated electrons are limited to pass through the cell only to a desired direction. For example, such device was successfully built on the NiOx-ZnO homogeneous layer as reported by Zhu et al [19]. When a junction between two semiconductors is formed, the charge carriers (electrons in n-ZnO and holes in p-NiO) diffuse through the p-n interface causing the potential to increase until the flow flux caused by the potential and diffusion cancels out. This causes Fermi levels to align and the band edges of the semiconductor to adjust accordingly to reach thermal equilibrium and establish a space charge region with a built-in filed pointing from n-ZnO to p-NiO. In this way, when the generated electrons of cell and the intrinsic electrons of materials transport to the NiO/ZnO hetero-interface region, they are easily modulated by the built-in filed of NiO/ZnO heterojunction, for instance, being suppressing by the electric field. Thus, the SIM layer could gain significantly reduced electronic conductivity through the energy band alignment, as shown in an illustration below of Figure 4c. By using this feature, the electronic short-circuit risk of SIMs fuel cells (SIMFCs) could be avoided. As reported [19] such single layer device built on p-n junction semiconductors, in which NiOx and ZnO formed a homogeneous nanocomposite to provide the necessary electrochemical reaction sites and charge transport paths for a fuel cell. These can be accomplished via tailoring ionic and electronic (n, p) conductivities and catalyst activities to enable redox reactions occurring on nano-particles and ultimately accomplishing a fuel cell function. The p-n bulk-heterojunctions are associated with the ionic conductor (e.g. SDC: samarium doped ceria) that act alike an electrolyte layer to facilitate the charge transfer processes for ions (H+ and O2-) along with the electron-hole among involved p-, n- and ionic particles to realize the nano-redox SOFC built on the SIM materials.
Figure 4. (a): Illustration of conventional anode/electrolyte/cathode SOFC from a physical-electrochemical view as an p-i-n structure; (b): p-n junction double layer device by removing the ionic electrolyte layer; (c): a single-layer device based on nano-redox reaction principle with a bulk p-n- heterojunction and energy band alignment. CC: current collect; The schematic diagram of the nano-redox reaction mechanisms, where (d) is based on $\text{O}_2^-$ and $\text{H}^+$, (e) based on O and $\text{H}^+$, and (f) based on $\text{O}_2^-$ and H, respectively. (Copyright from 2013 Nano Energy. Including the following text (a), (b) and (c)). (CC: conduction band, VB: valence band, LSM: $\text{La}_{0.85}\text{Sr}_{0.15}\text{MnO}_3$)

In this single layer SIM device, the working principle of the nano-SOFC is proposed from three different nano-redox processes involving protons, oxygen ions or both, as well as H/H$_2$ and O/O$_2$, which may result in different fuel cell processes below, also illustrated in Figure 4 (d), (e) and (f), respectively:

i) Completed directly by $\text{H}^+$ and $\text{O}_2^-$ as shown in Figure 4(d):

Hydrogen side:
\[
H_2 \rightarrow 2H^+ + 2e^-
\] (1)

264 Air side:

\[
1/2 O_2 + 2e^- \rightarrow O^{2-}
\] (2)

265 Total reaction:

\[
H_2 + 1/2 O_2 \rightarrow H_2 O
\] (3)

266 ii) Completed by \(H^+\) and \(O\) atom (or \(O_2\)) as shown in Figure 4e:

267 Hydrogen side:

\[
H_2 \rightarrow 2H^+ + 2e^-
\] (4)

268 Air side:

\[
2H^+ + 1/2 O_2 + 2e^- \rightarrow H_2 O
\] (5)

269 Total reaction:

\[
H_2 + 1/2 O_2 \rightarrow H_2 O
\] (6)

270 iii) Completed by \(O^{2-}\) and \(H\) atom (or \(H_2\)) as shown in Figure 4(f):

271 Hydrogen side:

\[
H_2 + O^{2-} \rightarrow H_2 O + 2e^-
\] (7)

272 Air side:

\[
1/2 O_2 + 2e^- \rightarrow O^{2-}
\] (8)

273 Total reaction:

\[
H_2 + 1/2 O_2 \rightarrow H_2 O
\] (9)

As there seems to be several paths to realize the nano-redox reactions discussed above, which also opens up more possibilities to find optimal materials and design micro-structure to realize the nano-SOFC under on-going research and development. It should be noteworthy that even though each individual reaction above at nano-scale has not yet been verified due to experimental limitations, all possible reaction routes and redox pathways formulated by Equations (1-9) should theoretically be considered. They lay a foundation for nano-SOFCs based on nano-redox processes and mechanisms.
5. Materials and technologies

The aforementioned new type of nano-SOFC mainly relies on a single layer of SM/SIM to realize nano-redox processes to complete fuel cell reaction, which is quite different from that of conventional SOFC, thus indicative of new material system and technologies. Such single layer fuel cell (SLFC) device was first demonstrated based on a homogeneous mixture of semiconducting oxides (NiO, ZnO) and ionic conducting oxides (SDC or GDC) [19, 20]. It was regarded as “three-in-one” device as the single layer can function simultaneously as electrolyte for ion transport and as electrodes for HOR and ORR processes [28]. Inspired by these studies, a sequence of electrode materials, especially p-type semiconducting perovskite oxides such as SrFeO$_3$, SrFeMoO$_3$, SrSmCoO$_3$, LaSrCoFeO$_{3-δ}$, and La$_{0.75}$Sr$_{0.3}$Cr$_{0.5}$Fe$_{0.5}$O$_{3-δ}$, were used to prepare the SIM or SMs with SDC/GDC and demonstrated successfully in SLFCs [22,23,29-31]. In parallel, metal oxides with layered structure were also applied in SLFCs individually or in heterostructure composite form, including p-type semiconductors LiCoAlO$_2$, NaFeNiO$_2$ and Ni$_{0.8}$Co$_{0.15}$Al$_{0.05}$LiO$_{2-δ}$, which have shown promising fuel cell performance [32-34]. Further studies explored new SM and SIM materials with better fuel cell performances based on various common n- and p-type semiconductors, such as, n-type ZnO [35, 36], n-type TiO$_2$ [37], n-type SrTiO$_3$ and La-doped SrTiO$_3$ [38,39], n-type CeO$_{2-δ}$ [40, 41] and p-type SiC [42], etc. Moreover, triple charge (H$^+$/O$^2-/e^-$) conducting materials, e.g. p-type BaCo$_{0.9}$Fe$_{0.1}$Zr$_{0.1}$Y$_{0.1}$O$_{3-δ}$ and Ba$_{0.5}$Sr$_{0.5}$Co$_{1.1}$Fe$_{0.7}$Zr$_{0.1}$Y$_{0.1}$O$_{3-δ}$ were also demonstrated in the single-layer device, exhibiting excellent fuel cell performances [43-45].

All these works have indicated a fact that SM and SIMs can be used as new functional membranes to replace the conventional ionic electrolyte of SOFCs. These significant findings have stimulated a strong interest in research and development of SM fuel cells (SMFCs) and SIMFCs. Moreover, studies on fundamental issues of SMFCs and SIMFCs have also been carried out with a focus on the avoidance of electronic short circuit issue, which is proved to be an inherent advantage introduced from using the SMs/SIMs to replace the conventional electrolyte membrane. The underlying
scientific mechanism and working principle for SMFCs and SIMFCs have been
discovered in terms of junction effects and energy band alignments within the devices.
For instance, bulk p-n heterojunction, planar p-n junction, and Schottky junction have
been taken into account as a major factor that leads to built-in-field for charge
separation, which can block the electrons from passing internally through the devices
and thus evade short circuit risk [20, 21, 46-48]. Based on these working principles,
various junction-based fuel cells and relative technologies have been emerged by
means of interface modulation method and energy band engineering [49].

Table 1 A summary of performance studies of fuel cell fabricated from various of
SIM and SM.
6. Future research and development.

Though the SOFC technology has been advanced over the last two decades, unleashing potential of SOFCs requires more attention to be paid on the operation of the commonly used YSZ electrolyte material which has limited ionic conductivity at lower temperatures. The nano-SOFC provides a new route to address this quest by taking advantage of nano-redox reaction principle and device. A remarkable benefit from the new approach eliminating a physically separated electrolyte layer deserves further investigations of nano materials based on SIMs and associated operational conditions in order to realize the great opportunities.

In this regard, the authors may propose a typical example for an advanced technology and future development in the nano-SOFC science may be a single-layer device made of triple charge (H+/O2-/e-) conducting oxides (TCOs) [45]. The TCOs have been frequently used as the electrodes in SOFCs in forms of simplex phase and heterostructure material for enhancing the cell performances via facilitating the HOR and ORR activity. Based on the nano-SOFC principle, the device can be directly built on the TCO single layer as presented by Figure 5. The TCO functions in this case like a membrane reactor, which can not only realize HOR and ORR on sites within the
TCO membrane, but also transport ions simultaneously to complete the fuel cell reactions. Due to the amphoteric semiconducting properties of the TCO, it displays either n- or p-type conductivity under reducing or oxidizing environment, respectively, in the fuel cell anode and cathode sides. Therefore, there is an in-situ formation of a spatial n-p bulk-heterojunction to prevent the electron short circuit problem, as illustrated by Figure 5, that enables a single-layer SOFC device composed of the nano-redox generators. The HOR and ORR can occur at any site in the TCO membrane layer to realize the fuel cell function. Since the TCO itself is a SOFC electrode, when a TCO membrane device is in operation status, electrons are activated to the conduction band (CB) and the holes to the valence band (VB), which can be transferred to anode zone and cathode zone as indicated in the illustration bellow of Figure 5, thus further promoting the fuel cell HOR and ORR reactions. Therefore, it can improve the electrocatalytic and redox reaction efficiency to make the device higher conversion efficiency and power output.

Figure 5. TCO single-layer fuel cell built on the nano-redox unit/reactor (an illustration above) and charge separation mechanism (an illustration bellow) (Ec: Energy of conduction band, Ev: energy of valence band, Ef: energy of Femi level, IEF: internal electric field).

It is worth noticing that the spatial p-n bulk-heterojunction of the TCO membrane device can provide several functions and contributions: i) to block the electron flow in the TCO membrane avoiding electronic short-circuiting; ii) the direction of the p-n bulk-heterojunction built-in or internal electric field (IEF) distributed over the TCO
membrane, as illustrated in an illustration below of Figure 5, excels the transport of the ions, e.g. H\(^+\) and O\(^2-\), thus increases the ionic conductivity and output current/power; iii) the TCO membrane itself is as equivalent of the electrode available in traditional SOFCs, so it can attend and promote the fuel cell redox reaction simultaneously; iv) minimized or even avoided the interface polarization that are critical for traditional SOFCs. All these features support the uniqueness and advances of the TCO membrane fuel cell.

The fuel cell device built on the TCO single-layer can therefore reach a high efficiency and expected power output > 1000 mWcm\(^2\) at \(\leq 500\) °C due to its efficient on-site redox reactions and charge transfer/transport, as well as the high ionic mobility accelerated by the IEF. Because of its rather simple structure, low cost of materials and easy fabrication and manufacturing of the devices, the traditional SOFC’s associated multi-component structure, the complexity, and the burden of matching chemical and physical compatibility as well as the high fabrication cost problems can be eased or even totally avoided. Moreover, superior performances in the desired temperature range, e.g, 300-500 °C, can well be expected for the realistic demonstration of low temperature SOFC/PCFC operations. The authors believe that the TCO based nano-SOFC science may offer a new research and development avenue for commercialization of the SOFC/PCFC technology.

At present, the SMFCs/SIMFCs are still in the research stage, with constraints in terms of engineering natures and financial supported technical projects, limiting the scope of the collected data for reviewing the technical and engineering issues. However, some important analysis can be performed with respect to the material and technological aspects to strengthen the viability of the SMFC/SIMFC systems. Though current studies of SMFC/SIMFC have primarily focused on laboratory-scale single cells to attempt new semiconductors or semiconductor-ionic materials for membrane applications, two major aspects can be availably evaluated: i) the SMFCs/SIMFCs commonly deliver higher electrochemical performance compared to the conventional SOFCs at low operating temperatures; ii) operation durability with 100-200 h of the SMFCs/SIMFCs have been successfully demonstrated, which have
strongly proven the feasibility of the new working principle of SMFCs/SIMFCs as discussed earlier. Table 2 lists the latest reported durability of SMFCs/SIMFCs for over 100 h. Moreover, the SMFC/SIMFC devices can be fabricated in a simplified structure to avoid the complex procedure for conventional anode/electrolyte/cathode assembly, even as a single layer device. Therefore, both material and manufacturing costs can be significantly reduced.

Table 2: A summary of stability investigation of some typical SMFCs and SIMFCs. (SCDC: Sm/Ca co-doped CeO₂, LCP: La/Pr co-doped CeO₂)

<table>
<thead>
<tr>
<th>Semiconductor Membrane</th>
<th>Temp. (°C)</th>
<th>Current density (mA cm⁻²)</th>
<th>Stable hours (h)</th>
<th>Years</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>La₀.₆Sr₀.₄Co₀.₂Fe₀.₈O₃₋δ-SCD</td>
<td>550</td>
<td>179</td>
<td>~60</td>
<td>2017</td>
<td>50</td>
</tr>
<tr>
<td>NiO-YSZ-La₀.₆Sr₀.₄Co₀.₂Fe₀.₈O₃₋δ</td>
<td>550</td>
<td>115</td>
<td>&gt;100</td>
<td>2018</td>
<td>51</td>
</tr>
<tr>
<td>Core-shell CeO₂/CeO₂₋δ</td>
<td>520</td>
<td>100</td>
<td>~200</td>
<td>2019</td>
<td>41</td>
</tr>
<tr>
<td>BaCo₀.₂Fe₀.₁Ce₀.₂Tm₀.₁Zr₀.₃O₃₋δ</td>
<td>530</td>
<td>120</td>
<td>~100</td>
<td>2021</td>
<td>45</td>
</tr>
<tr>
<td>Ba₀.₅Sr₀.₅Fe₀.₈Sb₀.₂O₃₋δ-SDC</td>
<td>520</td>
<td>110</td>
<td>&gt;100</td>
<td>2021</td>
<td>52</td>
</tr>
<tr>
<td>CeO₂-Na₂CO₃ coating layer</td>
<td>500</td>
<td>100</td>
<td>~100</td>
<td>2021</td>
<td>53</td>
</tr>
</tbody>
</table>

From material and technical aspects, compatibility issues still exist due to the lack of suitable electrode materials which have good chemical and mechanical compatibilities with the semiconductor-based membranes. This has actually been a long-existing issue in the conventional SOFC technology over several decades until the perovskite electrodes with proper compatibility with YSZ electrolyte have been developed through suitable fabrication techniques. It is generally accepted that for these novel SMFCs/SIMFCs, significant technical and engineering bottlenecks still remain that prohibit the further scale-up of this fuel cell technology. But there is enormous
ongoing research to increase fuel cell performance by exploring new semiconductor or semiconductor ionic materials with the potential to be applied for industrial purposes. Another distinct characteristic is the low-temperature (< 550°C) operation superiority of SMFC/SIMFC over the intermediate-temperature (> 600°C) SOFCs or the commercial systems that typically operate above 700°C, which allows knock-on benefits in terms of low-cost interconnect and the sealant to be adopted, lowering investment while providing better durability. Therefore, the total cost of the cell is expected to be effectively reduced, making it more competitive in the energy conversion market. However, it is noteworthy that the development of SMFC/SIMFC is still in its early stage with material and technological restrictions, as frequent approaches for developing conventional SOFCs are not perfectly applicable for SMFCs/SIMFCs. Therefore, more efforts are required worldwide from academic researchers of various backgrounds/fields to elucidate the underlying science. In addition, inputs from the industrial stakeholders are urgently required and the policy supports from government are crucial to accelerate the pace of technological transfer of SMFCs from the lab-scale to industrial pilot plant demonstration, to achieve its early techno-economic target for the commercialization.

DECLARATIONS

Authors’ contributions

Wrote and reviewed the manuscript: Zhu B, Mi Y, Xia C, Wang B, Kim JS, Lund P, Li T

Availability of data and materials

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Conflicts of interest

All authors declared that there are no conflicts of interest.

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