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# Interconnect Development for Solid Oxide Fuel Cell Application

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**ABSTRACT**

Solid oxide fuel cell (SOFC) is a green and reliable alternative energy source. Recent developments in SOFC have reduced its operating temperature from high (>1000 °C) to intermediate (<800 °C), thereby replacing ceramics by metal alloys as interconnect materials. Strict criteria in selecting interconnect material lead to Cr-based alloys as potential candidates, especially ferritic stainless steel (Fe-Cr-). Fe-Cr- possesses electrical conductivity, malleability, and low cost but it undergoes fast chromia scale growth rate, which leads to gaseous Cr species migration when exposed to high temperature (>800 °C); the gas will cause poisoning on cathode, leading to cell degradation. To overcome this issue, protective coating is used as a barrier to prevent the gaseous Cr species from surfacing. Among the coatings that have been used in previous studies, spinel coating, especially (Mn, Co)3O4, exhibits the best performance in terms of coefficient of thermal expansion (CTE) and area specific resistance in long SOFC operation. A dopant, such as Cu, is added into the Mn–Co composition to improve the electrical conductivity and CTE of the coating.



## 1. Introduction

Research on solid oxide fuel cell (SOFC) began more than a century ago and is continuously developed at present. SOFC has elicited considerable research interest due to its ability to produce electrical energy via chemical reaction without any combustion or mechanical processes, thereby making it green energy [1-3]. As shown in Figure 1, a single SOFC comprises three main components, namely, cathode, anode, and electrolyte. SOFC operates at high temperatures of approximately 600 °C to 1000 °C for electrochemical reaction to occur.

At high temperature, hot air is supplied to the cathode, whereas steam is mixed with fuel, thereby forming a reformed fuel that is supplied to the anode. When the fuel enters the anode, it attracts the oxide ions that were reduced at the cathode, as shown in Equation (1). These ions are combined with

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fuel to produce electron and small portion of water, as shown in Equation (2). The water is recycled to produce steam, which is needed to reform fuel. This process also generates heat, which is needed by the SOFC. Therefore, if air and heat are present, this process will continuously produce clean, reliable, and efficient electrical energy.

$$O_2 + 4e^- \rightarrow 2O^{2-} \quad (1)$$

$$2H_2 + 2O^{2-} \rightarrow 2H_2O + 4e^- \quad (2)$$

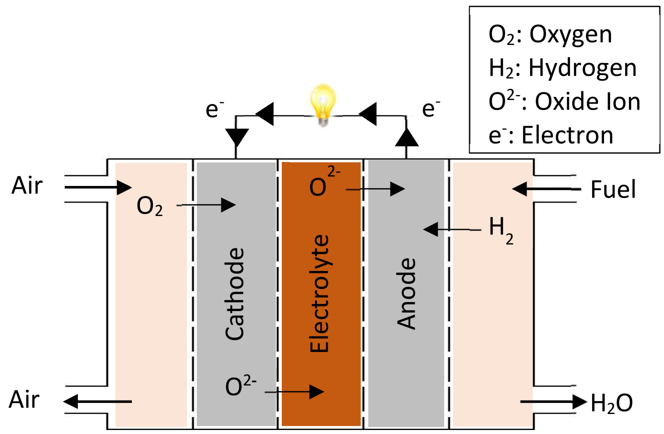

**Fig. 1.** Schematic of SOFC operation and components

In most applications, SOFC must be developed in stacks to fulfill the power requirement of the application operation. Hence, each single cell is connected using an interconnect. Figure 2 shows the SOFC planar design. The interconnect function conducts electricity between the cell and separates the fuel and oxide gas from mixing [4]. For excellent performance, stringent criteria must be met in selecting the interconnect material, such as excellent oxidation resistance, good electrical and heat conduction, and suitable coefficient of thermal expansion (CTE) [5-7].

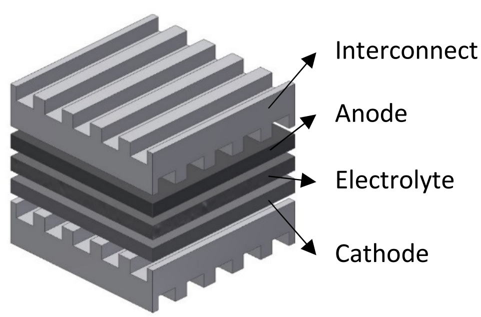

**Fig. 2.** Schematic of SOFC planar design

Ceramic is traditionally used as an interconnect material due to its high heat resistance. However, development on thinner electrolyte has reduced the operating temperature of SOFC to the range of 600 °C to 800 °C [8-10]. Thus, researchers have pursued opportunities to lower the fabrication cost by using materials such as metal alloys. In comparison with ceramics, metal alloys have higher oxidation resistance, better heat and electrical conductivity, and better manufacturability and mechanical strength [11-13]. This paper focuses on the potential metal alloy candidates, including their issues, such as chromium poisoning and the use of protective coating to overcome it; these are further discussed in the subsequent sections.

## 2. Metallic Interconnect

Although various of metal alloys exist, previous studies have revealed that potential candidates can form alumina ($Al_2O_3$) layer or chromia oxide scale ($Cr_2O_3$) continuously. Such capability important in providing oxidation resistance under SOFC operating conditions [14]. Based on the previous literature [15], metals that contain chromium (Cr) such as Cr-, Fe-Cr-, and Ni-Cr-based alloys have natural $Al_2O_3$ resistance, thereby making them suitable potential interconnect materials [16]. However, Cr- content in metal can affect its electrical performance and oxidation resistance.

Yang *et al.,* [17] reported that high concentrations of Cr- (>23%) can reduce contact resistance and oxide scale growth, whereas low Cr- content (<5%) leads to low oxidation resistance and increased electrical resistance [18]. Therefore, ferritic stainless steel (Fe-Cr-) is the best candidate compared to the others due to its optimum Cr- content [19]. Furthermore, the body-centered cubic structure of the steel provides CTE compatibility with other SOFC components [20], which is important to avoid spallation or cracks because of mechanical stress produced from thermal cycling [21].

Aside from the advantages mentioned, ferritic stainless steel, however, is exposed to chromia scale growth at elevated temperature. In addition, this scale can grow up to tens of micrometers after thousands of hours of exposure of interconnect to SOFC environment with intermediate temperature (~800 °C) [22]. Long exposure of the alloy to high temperature causes the chromia scale to grow continuously, which increases electrical resistance. Further exposure will lead to spallation of the scale and cracks due to thermal cycle during SOFC operation [23]. Consequently, the chromia scale growth also results in thermodynamic instability, which leads to migration of Cr (IV) gas species, such as chromium oxide ($CrO_3$) and chromium oxyhydroxide ($CrO_2(OH)_2$) [24].

$$2Cr_2O_{3(s)} + 3O_{2(g)} \leftrightarrow 4CrO_{3(g)} \tag{3}$$

$$2Cr_2O_{3(s)} + 3O_{2(g)} + 4H_2O_{(g)} \leftrightarrow 4CrO_2(OH)_{2(g)} \tag{4}$$

$$Cr_2O_{3(s)} + O_{2(g)} + H_2O_{(g)} \leftrightarrow 2CrO_2(OH)_{(g)} \tag{5}$$

Cr gas migration depends on the partial pressure and water content of oxygen, where the reaction is negligible at the anode due to a lower homogenous gas pressure of Cr–O–H (between $10^{-10}$ Pa and $10^{-14}$ Pa) compared with the cathode (between $10^{-6}$ Pa and $10^{-9}$ Pa) [25]. Therefore, Cr gas poisoning is higher at the cathode where the Cr (IV) species is formed via reactions, as shown in Equations (3), (4), and (5) [26]. The mechanism and kinetics of the Cr poisoning on the cathode can occur in two circumstances [27]. The first theory is that Cr gas migration will either be reduced electrochemically or that chemical precipitation occurs at the three-phase boundary, thereby forming a barrier at the active area of the cathode [28]. Second is the nucleation theory, which occurs at the electrode surface, electrolyte, and the interface between the two components [29]. Either way, both theories lead to prevention of oxygen reduction reaction into oxide ions and results in cell degradation. To prolong the cell lifetime, researchers have focused on suitable coating development to overcome the issue.

## 3. Protective Coating

Previous research shows that gaseous Cr species migration can be reduced by using protective coating on the interconnect. The coating also helps in reducing electrical resistance and improving rust resistance [30]. Three types of materials are widely used in previous studies, which are rare earth perovskite, reactive oxide elements, and spinel oxide composite. However, spinel coating attracts the most interest among researchers because it can prevent gaseous Cr species migration from chromia scale to the surface and has lower cost compared to other types of coating material (Figure 3) [31-33]. Spinel coating, especially $(Mn,Co)_3O_4$, exhibits good performance in terms of area specific resistance stability and Cr gas prevention during long-term SOFC operation [34-37].

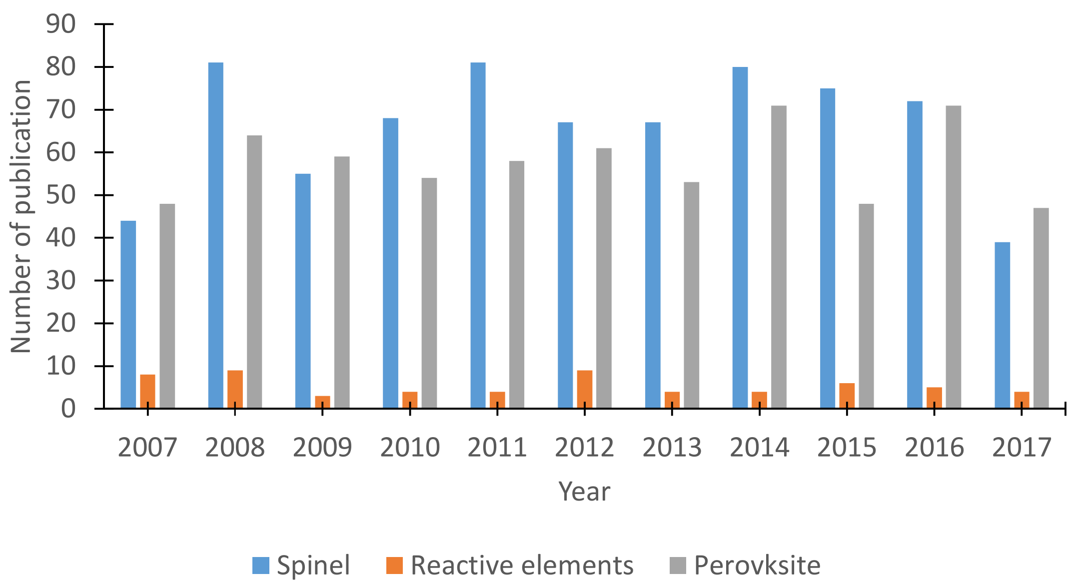


**Fig. 3.** Publication on different types of coating in the past 10 years (Keywords: "SOFC," "interconnect," "spinel," "reactive element," and "perovskite" in http://www.sciencedirect.com, May 2017).

Dopants, such as copper (Cu) or nickel (Ni), are added to the spinel Mn–Co composition to develop the coating performance further. The addition improves the electrical properties and adherence of the coating to the interconnect [38,39]. Xu *et al.,* [40] reported that adding dopant, especially Cu, can lower the sintering temperature and further match the CTE of the coating to the ferritic stainless steel interconnect. Consequently, Cu dopant can reduce the Co element usage in the spinel coating, which has high cost and toxicity [41]. However, aside from the use of dopant, other factors, such as coating technique, also exert a significant effect on the final performance of the coating. Thus, research on this aspect is also the main focus to improve the interconnect coating.

## 4. Coating Technique

One of the challenges for SOFC is the fabrication cost, which prevents its commercialization [42]. Therefore, low-cost coating method is preferable to avoid further increase of SOFC fabrication cost. Many interconnect coating techniques have been used in previous studies, such as chemical vapor deposition, physical vapor deposition, sol–gel, plasma spray, magnetron sputtering, and electrophoretic deposition (EPD) [43]. Among these techniques, EPD is well known in the research and industry sector due to its various material combinations, uniform layer deposition on complex shape, and low equipment cost [44]. Hence, the interconnect can be fabricated in more complex shapes to develop the SOFC performance.

EPD is one of the colloidal techniques that offers easy control on layer thickness and morphology [43]. Figure 4 shows the basic EPD setup. Cabanas-Polo and Boccaccini [45] reported that compared to other methods, EPD has the advantages of standard temperature and pressure process condition, simple control on the nanoparticle, and environment friendly solvent. However, EPD parameters vary depending on the material. Thus, further research is needed when using new materials, such as Cu-doped spinel coating, especially in preparing a stable suspension because of its critical role in successful EPD.

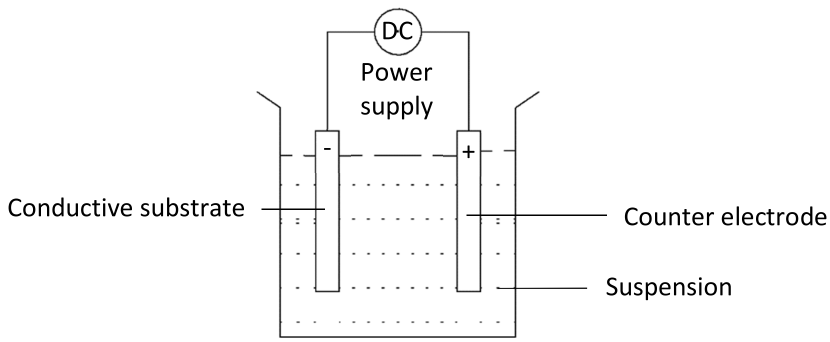


**Fig. 4.** Schematic of cathodic EPD set up

## 5. Conclusion

Ferritic stainless steel has been well established as an interconnect material. However, it can cause Cr poisoning on the cathode, which reduces the SOFC lifetime. Hence, coating is introduced to overcome the problem, in which Cu-doped spinel coating is the best candidate due to its optimum performance. Nevertheless, simple and low-cost methods must be considered, such as EPD, to prevent from increasing the fabrication cost. Despite its advantages, research on EPD remains limited; thus, further study is required to understand its fundamental mechanisms and key parameters in producing a dense and uniform coating.

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