Nanoscale Architectural Engineering for High Performance Solid Oxide Fuel Cells

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Objective
The goal of this research is to develop a methodology, including design rules, manufacturing techniques and material formulations, for building the membrane electrolyte assembly (MEA) of a solid oxide fuel cell (SOFC). As new materials are discovered and nanoscale engineering methods are refined, opportunities to drastically improve the performance of SOFCs become available because those advances multiply each other's benefits. This project seeks to incorporate the results of the latest SOFC research into a new design paradigm, free of the engineering compromises that were made for the previous generation of SOFCs.

Background
It has been shown, both in theory and at the laboratory scale, that SOFCs are capable of performing hydrocarbon-to-electricity conversion at almost twice the efficiency of widely deployed electricity generation equipment. However, the cost of SOFCs has limited their ability to penetrate the power production market. Roughly, the cost of a fuel cell is linearly proportional to the total area of its MEA. The area of MEA required, however, is inversely proportional to the maximum current density sustainable through the MEA. Consequently, the price of fuel cells can be reduced significantly if current density can be increased without increasing the cost per unit MEA area.

In order to achieve a given level of performance, each component of the MEA (anode, electrolyte, cathode and gas-exchange networks), must be able to handle the required current density. The present generation of SOFCs runs at a current density of approximately 400mA/cm². This number approaches the limit for today's electrolytes, but if the thickness of the electrolyte could be reduced by a factor of 10, and its conductivity increased by a factor of 3, a 30-fold increase in permissible current density could be achieved.

The limit to current density imposed by the anode and cathode is a product of the catalytic activity of the electrode material and the number of active sites per unit MEA area. It is expected that the feature size of catalyst particles can be reduced by a factor of 20, improving the current-density limit over today's electrodes by a similar margin.

The gas-exchange networks at the air- and fuel-sides of the MEA must be designed for high porosity and low tortuosity. Present-day SOFC electrodes are not optimized for low tortuosity because the inherent limits of the gas-exchange networks are rarely reached. It is expected, however, that if high current-density electrolytes and catalysts are developed, the gas exchange networks will need to be re-engineered. An optimally designed network should be able to accommodate the target value of 10 A/cm².
**Approach**

An ultra-thin, ultra-high conductivity electrode will be fabricated via solution and/or chemical vapor deposition. These methods not only provide the means to precisely control thickness, they also limit the conductivity loss caused by grain boundaries and impurities. Gadolinia doped ceria or samaria doped ceria will be used because those materials exhibit the highest oxygen-ion conductivity at low SOFC temperatures (900K).

On either side of the electrolyte membrane, a highly open, non-tortuous, graded pore-size electrode will be built (Figure 1). On the anode side, the structure will be built from the same material as the electrolyte, while on the cathode side, another material such as the cathode catalyst will be used. The engineered structure depicted is similar to an inverse opal structure (Figure 2) which can be engineered at the micro- and nano-scales from commercially available sacrificial polystyrene spheres. Seed particles for nanowire growth can be evenly distributed throughout the structure using block copolymer lithography. From these seeds, nanowires and catalyst particles will be grown via chemical vapor deposition, resulting in a forest of nanowires (and its associated high surface area) throughout the three-dimensional electrode.

The resulting structures will be completely characterized via thermogravimetric analysis, x-ray powder diffraction, raman spectroscopy, electron microscopy impedance spectroscopy and other methods. These material analyses and performance data will confirm the relationship between high current density and nanostructural engineering.

**Figure 1:** Schematic of an MEA with non-tortuous, high-surface area electrodes

**Figure 2:** Inverse opal structures constructed from CeO$_2$-YSZ (Dunn and Haile, 2006, unpublished)