

A MICRO FUEL CELL STACK WITHOUT INTERCONNECT OVERHEAD – MACRO WORLD-LIKE STACKS IN MEMS

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Abstract — This paper describes a unique method for vertically stacking microfabricated fuel cells (MFC). Both electrical and fluidic interconnects are reduced to a minimum, and the stacking can be continued without increasing the complexity of the structure. The method allows for a practically unlimited number of elements in the vertical stack. A two-cell stack has been fabricated and the results are reported proving the viability of the design.

Keywords : Micro fuel cell, Black silicon, Stacking, Proton electrolyte membrane, Proton exchange.

I - Introduction

Microfabricated fuel cells (micro fuel cells, MFC) are a promising emerging technology for powering portable electronic devices (mobile phones laptops, camcorders etc.) [1]. The promise lies in the higher energy density of fuel cells, compared to lithium-ion batteries. In this context, a microfabricated power source should, in order to be a good replacement for traditional batteries, have the same or smaller total volume (and/or weight), yet same or higher total energy. This volume includes both the fuel reservoir and the MFC itself. Because micro fuel cell operating temperatures are typically lower than with macro fuel cells, the power density per unit volume in MFCs is usually considerably smaller. To make up for this deficiency, one could take advantage of the miniaturization of MFCs, and simply have more of them in the same package. So if a MFC has a power density of 1 mW cm⁻² but has an overall thickness of 1 mm, then stacking n of such cells would yield an effective power density of n mW cm⁻², within a n mm thick fuel cell stack. The benefit of stacking increases when the thickness of a cell is smaller. We have previously demonstrated a simple, vertically compact MFC [2], which is a good candidate for stacking.

Another advantage of vertical stacking of fuel cells compared to planar stacking is the reduction of total surface to volume ratio, which is a significant factor for thermal confinement of the fuel cells. In [3] a solid oxide MFC is stacked for this purpose: the operating temperatures are in excess of 500°C, and it is important to both keep them at these levels to further the electrochemical reactions, and to shield the user from these temperatures. This design, however, does not permit to

stack more than two fuel cells vertically, unless an electrical interconnect network is added, increasing assembly costs and total volume, and adversely impacting thermal confinement.

Existing literature on the topic of MFC stacking reveals a conspicuous lack of vertically stacked designs, while a much larger number of publications describe planar stacks such as in [4 – 7]. This is in spite of the fact that planar stacks offer very little in terms of area-to-volume reduction (compared to a single cell), require more overall thermal insulating material and/or structures, and are more restricted by the form-factor of the mobile device that houses them. The reason for such a disproportion in scientific literature lies in the complexities of microfabricating fluidic and electric distribution networks. Planar designs generally eliminate either the need for microfabricating the fluidic or the electrical interconnect network, but not both. On the other hand, in macro fuel cells, the overhead of electrical and fluidic pathways is small, and there the vertically-stacked fuel cells are the norm.

In [3] the issue of fluidic distribution is eliminated by using a single-chamber design, where fuel and oxidant are mixed together, but requires higher operating temperatures. In [8] the problem is somewhat mitigated by sharing a single anode flowfield for two cells. Even in the two-cell setup that is described in the article, there are external fluidic channels, and their number would further increase if more cells were to be added to the stack.

In this paper we present a novel method for the creation of MFC vertical stacks, with virtually no overhead for electrical interconnects nor for fluidic channels, enabling one to add an arbitrary number of cells to the stack, without worrying about the microfabrication of such distribution structures.

II - Experimental Details

A. Design and fabrication

The design and fabrication of the device is essentially identical to the one reported earlier [2], apart from the placement of the gas inlet holes (Figure 1) and the requirement for holes in the polymer electrolyte membrane (PEM). These holes, together with a rotationally-symmetric placement of the fuel cell stack elements, constitutes the main idea of the present work. As can be

seen on Figure 1, a cell is constructed by tightening a Nafion® PEM between two electrodes. The fuel and oxidant flow channels and the gas diffusion layer (GDL) have both been fabricated with deep reactive ion etching (DRIE) of silicon; the GDL is made of nanograss (black silicon) created by anisotropic plasma etching under high oxygen flow in O_2/SF_6 etch chemistry. Nanograss increases silicon surface area and the number of triple junction points between electrode, reactant and electrolyte, as reported in [2]. The PEM is coated with carbon-supported platinum nanoparticles on both sides, using a modification of the method developed by Wilson and Gottesfeld [2, 9].

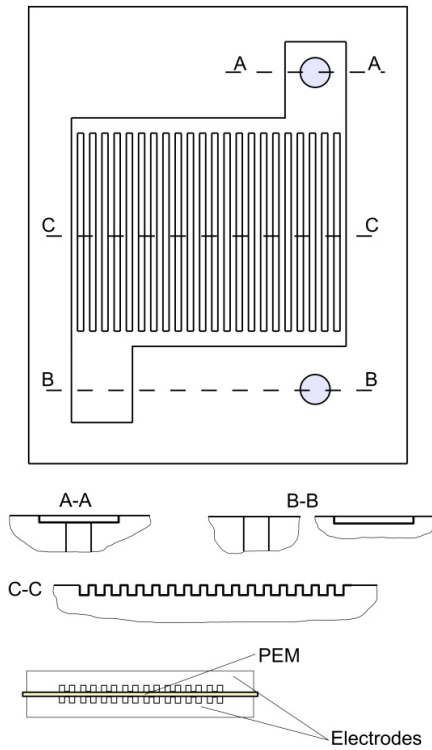


Figure 1: Micro fuel cell electrode and construction.

The gas inlet holes are 1 mm in diameter, while the flowfield area is $1.5 \cdot 1.5 \text{ cm}^2$, and the area of the silicon electrode is $1.9 \cdot 2.8 \text{ cm}^2$. The overall thickness of a cell is below 0.8 mm (2 wafers 300 μm thick plus Nafion® PEM).

The microfabrication process for the silicon electrodes has been described in much detail in [2], so only a brief overview will be given here. The fuel and oxidant flow channels and the gas diffusion layer (GDL) have both been fabricated with deep reactive ion etching (DRIE) of silicon; the GDL is made of nanograss (black silicon) created by anisotropic plasma etching under high oxygen flow in O_2/SF_6 etch chemistry. Nanograss

increases silicon surface area and the number of triple junction points between electrode, reactant and electrolyte, as reported in [2]. The fabrication steps are (Figure 2): A thermally oxidized, highly doped (0.01 $\Omega \text{ cm}$) silicon wafer (Figure 2) is patterned with photolithography and HF etching (2a) to determine the area affected by black silicon etch. Thin resist (AZ1505) is then spun and patterned (2b) to act as a mask for a deep RIE step (2c) thus bulk-micromachining a 30 μm deep flowfield. To create the gas inlets, aluminum is sputtered on the back side and patterned to form a mask for a deep RIE etch through the wafer (2d). The unprotected top silicon surface is then etched to form the nanograss, which is sputter coated by a thin layer of chromium (2e).

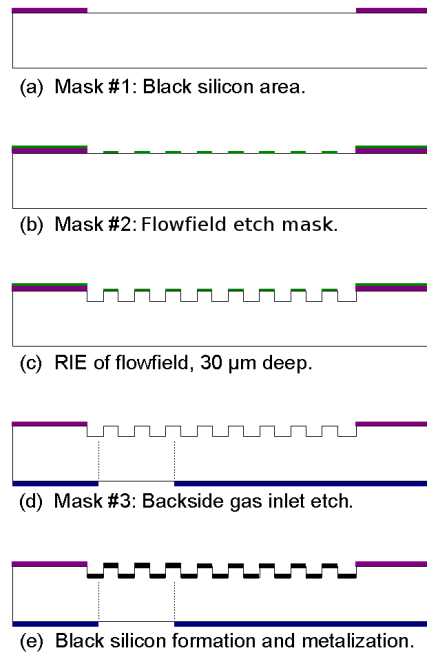


Figure 2: Microfabrication steps of silicon chip.

B. Stacking

As was mentioned above, the idea for our stackable design centers on the existence and placement of holes in the electrodes and the PEM, and their position with respect to each other. This placement and the resulting fluidic flows are depicted on Figure 3. Note that, with the choice of flow topologies for the fuel and the oxidant as in Figure 3, the upper electrode becomes the anode and the lower the cathode.

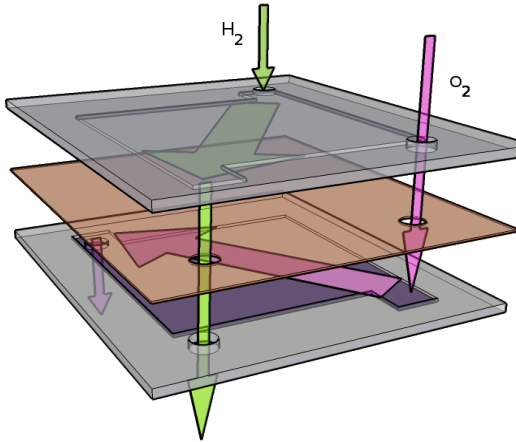


Figure 3: Gas flow through the flowfields of a top and a bottom electrode.

Figure 4 illustrates the principle of operation, in the case of a two-cell stack. It is very beneficial that, using this topology, the cathodes and anodes in a stack always face each other, rendering the addition of an external electrical interconnect network unnecessary. Every cell is rotated 180° with respect to the following and previous cell. By following this pattern, an unlimited number of cells can be added, without increasing the electrical and the fluidic interconnect overhead, because there is no such overhead at all.

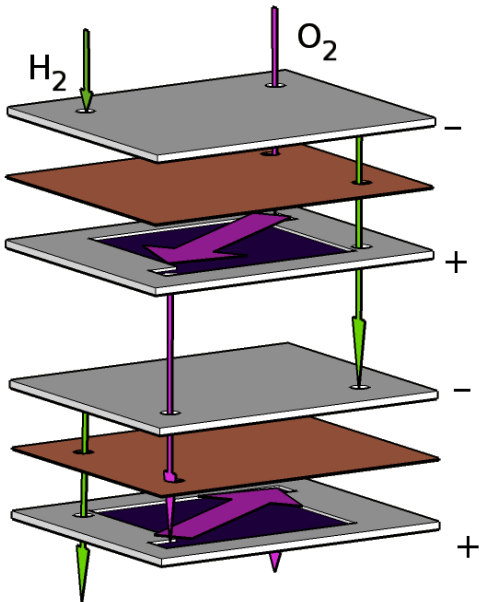


Figure 4: Illustration of a two-cell stack.

C. Measurements

The stacks were tightened together in a purpose-built jig with gas inlets and electric sockets for the measurement equipment. The fuel and oxidant were humidified, room-temperature hydrogen and oxygen respectively, flowing at a rate of 50 ml min⁻¹. The stack is electrically loaded by a computer-controlled potentiostat, and the voltage traverses the interval from open-circuit voltage (OCV) down to 100 mV.

III - Results and Discussion

An initial result of the measured open-circuit voltage for a two-cell stack was 1.8V, and a maximum current density of 11.8 mA at 100 mV was obtained. The current density is about an order of magnitude smaller than the one obtained for a single cell [2], while the OCV is clearly double that of a single cell. Figure 5 shows a plot of current and power densities for a two-cell stack.

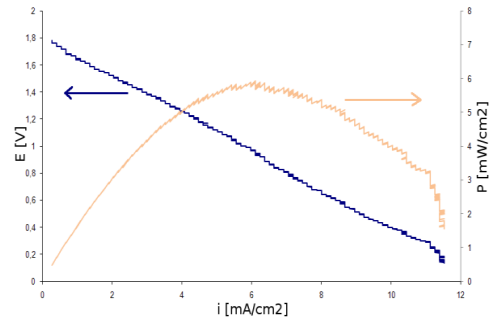


Figure 5: Measurement results of a two-cell stack electrical performance.

The reasons for the lower current density of the stack compared to the single cell design include considerable gas leakage and some ohmic losses in the stack. Both of these were a consequence of insufficient force applied on the stack to keep the elements together. During humidification, the Nafion® membrane would swell and warp irregularly, and the force necessary for eliminating the resulting leaks would cause the silicon chips to fracture.

IV - Conclusion

Vertically stacking of fuel cells, while simple and commonplace at the large scale, becomes challenging at the microscale. The volume of electric and/or fluidic interconnects becomes comparable to that of the MFCs themselves, and adds to the fabrication cost. Research has, until now, mostly focused on planar stacks, which require more packaging per cell compared to vertical stacks, higher area-to-volume ratio and may be incompatible with some portable device form factors. In this work, we have eliminated the overhead of fluidic and

electrical interconnects. The measurement results are, in spite of lower current density compared to single cells, encouraging. There are several avenues that will lead to increased current density from the proposed design: reduction of the flowfield area will make the electrodes mechanically more robust, which will allow for higher forces to tighten down the stack and reduce the ohmic losses and the gas leakage. Ohmic losses can also be further reduced by patterning both sides of each electrode, making it effectively both a cathode and an anode. This would also further decrease the overall height of a stack. Furthermore, a reduced area fuel cell implies also a Nafion® membrane of smaller area, which leads to lesser warping and again, lesser leakage. Bonding materials will also be tried, which will also reduce or perhaps even eliminate the gas leaks.

The design described here is a promising new tool in the hands of MFC researchers that aim at multi-cell structures while maintaining a simple interconnect and fluidic flow layout, allowing them to concentrate on the improvements of electrochemical and fluidic properties of the fuel cells.

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