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A hybrid sequential deposition fabrication technique for micro fuel cells

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Abstract
Micro fuel cell systems have elicited significant interest due to their promise
for instantly rechargeable, longer duration and portable power. Most micro
fuel cell systems are either built as miniaturized plate-and-frame or
silicon-based microelectromechanical systems (MEMS). Plate-and-frame
systems are difficult to fabricate smaller than 20 cm^3. Existing micro fuel
cell designs cannot meet the cost, scale and power requirements of some
portable power markets. Traditional MEMS scaling advantages do not apply
to fuel cells because the minimum area for the fuel cell is fixed by the
catalyst area required for a given power output, and minimum volume set by
mass transport limitations. We have developed a new hybrid technique that
borrows from both micro and macro machining techniques to create fuel
cells in the 1–20 cm^3 range, suitable for cell phones, PDAs and smaller
devices.

1. Introduction

Micro fuel cell systems are small fuel cells targeted at battery
replacement. These fuel cells generally produce between 0.5
and 50 W of power. The term micro fuel cell has also been used
to describe a fuel cell fabricated using MEMS technology. In
this paper we use micro to describe a small fuel cell intended
for use in portable applications, fabricated with a combination
of thin- and thick-film processes.

Micro fuel cell systems can benefit from MEMS
technology, because they are small electrochemical reactors.
However, the ultimate size of a micro fuel cell is dictated by
the required power, and surface area necessary to generate it.
For example, given operating conditions and materials, which
would deliver 250 mW cm^{-2}, a 1 W fuel cell must cover 4 cm^2
of surface area. Furthermore, because any parasitic loss must
be deducted from the total power produced, large pumping
loads due to small hydraulic diameters must be avoided [1].
McClean *et al* provide an excellent overview of the limitations
affecting micro fuel cell size from a materials viewpoint [2].

Because of the constraints of chemistry, materials and
manufacturing, micro fuel cells cannot benefit from the same
scale reduction economies as many other MEMS systems
such as sensors and biological analysis systems [3]. We have
developed a new micro fuel cell design and technique, which,
like the fuel cell itself, draws from both MEMS and continuous
manufacturing techniques [4].

Kelly *et al* reported a micro fabricated fuel cell in 2000
[5]. By creating a micromachined porous silicon substrate,
they formed simple, 5 mm cells. The gold-coated silicon
substrate was hot pressed into a previously catalyzed Nafion
membrane, creating a cell. They reported a 60 mW peak
power using 0.5 M methanol at 0.2 l min^{-1} and air at
0.2 l min^{-1}. They published an updated article on their
micro-pore-based fuel cell topology [6]. They demonstrated
that micro fuel cells could compete with their larger cousins
reported in the literature with respect to current and power
density.

Hockaday *et al* described a fuel cell system which
reduced the cost of previous fuel cell systems by using vapor
deposition techniques directly on the membrane–electrode
assembly (MEA) [7]. The MEA was segmented by selectively
depositing proton-conducting membranes within a porous
substrate.

Sim *et al* proposed a very small micromachined fuel cell that could be used to power medical micro-sensors [8]. They used two gold-plated silicon plates etched as flow fields and pressed into a Nafion membrane similar to the Kelly cell, but with channels instead of pores. Gold traces acted as both a current collector and catalyst. They reported very poor performance, likely because they did not use an appropriate catalyst, and because their stochiometric (1:1) methanol–water solution would have led to massive methanol crossover.

Lee *et al* proposed a 'flip-flop' micro fuel cell design where both anode and cathode are present on a single face [9]. While the flip-flop design does provide ease of manufacturing for solid-state systems by allowing in-plane electrical connectivity, it complicates the gas manifolding. Instead of electrons being routed from front to back, gasses must be routed in crossing patterns, significantly complicating the fabrication process and sealing. Individual cells achieved peak power densities of approximately 20 mW cm^{-2}.

Meyers and Maynard gave an overview of different micro fuel cell design trade-offs in [10]. In particular, they analyzed the theoretical limitations of in-plane fuel cells, where anode and cathode are side-by-side, with an ionic bridge between them, similar to a field effect transistor configuration. While this form of fuel cell is very easy to manufacture using solid-state technology, they showed that its performance was inherently limited. They found that the monolithic, side-by-side design was limited to less than 5 W cm^{-3}, compared to the more traditional top and bottom design, which was limited to about 12 W cm^{-3}.

Min *et al* published a variant of the design first published by Lee *et al*. While maintaining the same general 'flip-flop' configuration, they used a spin-on form of Nafion to create the ionic conduction path [11]. They reported poor results, with current in the microamps range, and voltages below 0.4 V.

Heinzel *et al* reported a small fuel cell, carefully constructed out of traditional fuel cell materials such as carbon paper and graphite, that can reach a peak power of 55 W with a four-cell stack, 20 ml min^{-1} hydrogen and 50 ml min^{-1} air [12]. While their power output was impressive, the cell was quite large, over 0.5 l in volume and weighing over a kilogram.

Ishida *et al* used a fiber optic inspired technique and created a micro fuel cell based on a Flemion tube [13]. The cathode was inside the tube and the anode was on the external face. While their design was novel, they achieved power densities of less than 1 mW cm^{-2} with methanol and air. Qiao *et al* investigated a platinum plating process for the fabrication of a micro tubular direct methanol fuel cell (DMFC) [14]. Flemion tubes were used as the substrate. The platinum black electrodes were deposited using a modified electrochemical plating process. A peak power density of 2 mW cm^{-2} was recorded. The CV analysis indicates that the platinum black is chemically active but the polarization curve indicates high activation and Ohmic losses.

D'Arrigo *et al* deposited porous chemical vapor deposition (CVD) silicon on top of a previously etched wafer, and spun-on Nafion in the resulting matrix to create a cell that required no assembly steps [15]. A cell-like structure was created, but no performance data were given. Their process did not require assembly, their fabrication process is long and complex requiring several sensitive CVD processes to achieve properly supported porous silicon.

Muller *et al* used micro structured metal foils instead of silicon or graphite to form the flow fields of their micro cell [16]. The flow fields were fabricated from 0.2 mm metal foils. Using Gore membranes, they were able to form very thin, high power density stacks. They demonstrated both uncompressed and compressed fuel cell designs. The uncompressed design had a peak power density of 20 mW cm^{-2} and the five cell compressed stack had a peak power density of 250 mW cm^{-2}.

Yu *et al* described a plate and frame cell with a slight modification to the current collectors [17]. By sandwiching copper between layers of gold, they were able to decrease the internal resistance of the thin-film current collectors, which corresponded to an increase performance of the fuel cell, achieving 193 mW cm^{-2} with H$_2$ and O$_2$.

Shah *et al* described a fuel cell similar in concept to our design but very different in implementation. In their implementation, sets of fuel cells are constructed on a bulk Nafion substrate by sequential depositions through a set of polydimethylsiloxane (PDMS) stencils [18]. The flow channels for the cell were subsequently produced by casting PDMS over a micromachined mold, and adhering the flow channels to the substrate. While their techniques were similar to ours, they only achieved 0.3 mW cm^{-2}, primarily due to the structure of their electrodes.

In recent research, Seo and Cho [19] proposed an alternative fabrication method for the flip-flop architecture of Lee *et al* [9]. Their proposal attempts to use MEMS techniques to fabricate the catalyst by using an array of micro-rods coated with platinum as the catalyst. While their research is an excellent example of micro machining, micro-rods make poor catalyst supports, because their surface area is low compared to the nanoparticulate platinum normally using in fuel cell electrodes. They were only able to achieve sub-milliwatt power.

The Stanford research team has developed a number of printed circuit board based fuel cells [20] similar to those in [12]. They used gold-plated copper as their electrodes, which presented an acceptable short-term solution. Testing with hydrogen and oxygen they achieved results consistent with large-scale fuel cell system, with power densities between 500 and 700 mW cm^{-2}. When using air instead of oxygen they achieved power densities of approximately 200 mW cm^{-2}.

Using a different fuel approach the team from the University of Illinois at Urbana-Champaign have designed a formic acid fuel cell [21]. Formic acid cells are similar to direct methanol cells, with formic acid having lower energy density, but better reaction kinetics than methanol. They used deep reactive ion etching (DRIE) to form the diffusion channels in the silicon substrate, and an electroplating technique to deposit the catalyst. They report power densities of approximately 17 mW cm^{-2}, respectable for a passive air-breathing fuel cell.

Some of the best micro DMFC results in the academic literature were reported by the University of California at Los Angeles, where they achieved 40 mW cm^{-2} using methanol and forced air [22]. They employed deep reaction ion etching to form bipolar plates in silicon, and then deposited a Ti/Cu/Au electrode with 3 μm of copper forming the bulk current collector. While the substrate will be stable as oxidized silicon, the electrodes are likely subject to corrosion over longer operating times.

Kubo, from NEC Research, described their efforts to create a direct methanol micro fuel cell around a carbon nano-horn (a truncated nanotube) as a catalyst support instead of the high surface area carbon usually used in fuel cells [23]. They suggest that increased performance due to increased surface area can lead to better power density and therefore smaller fuel cells. Peak power data of 1 W and 12 W for each fuel cell were disclosed, but the fabrication method, architecture and size of the fuel cell were not disclosed.

Young and Young described the fabrication of a micro pillar support for proton exchange membrane (PEM) cathodes [25]. The columns are fabricated using DRIE in silicon to fabricate electrodes. Platinum is sputtered on the columns to form the electrodes and the entire assembly is pressed into a bulk Nafion substrate. They compare the performance of their new electrode to the performance of a planar electrode. The planar electrode produced 5 μW cm^{-2} and the microcolumn electrode produced 122 μW cm^{-2} peak power.

The high aspect ratio UV-curable epoxy, SU-8, was used by Hsieh *et al* to created flow fields on a copper plate [26]. A copper sheet was coated with SU-8 which was patterned into flow fields. Silver was deposited on and around the risers to provide current collection from the top of the flow field rib to the copper substrate. Thin-film Pt on Nafion was used as an electrode. They report power densities of between 20 and 30 mW cm^{-2} using hydrogen as a fuel and forced and passive air at the cathode.

Cohen *et al* have taken a radically different approach to fuel cell design [27]. Rather than use a solid electrolyte the fuel cell takes advantage of the properties of laminar flow in microchannels. By using narrow channels with laminar flow, fuel, deionized and oxygenated water can be introduced as three laminar streams in a single channel. By depositing the electrodes on the sidewalls of the channel a fuel cell is formed with the DI water serving as the insulating electrolyte. While the approach is theoretically interesting, it is not practical for a real system because of the pumping loads and low oxygen content in water.

Employing a system similar to [17], Chan *et al* use flow fields micromachined in a spiral pattern using micro laser ablation of polymethylmethacrylate (PMMA) [28]. After ablation, gold is sputtered on the PMMA to provide a bulk current collector. Silver paint is deposited through a stencil on the surface of a carbon paper electrode in a grid pattern to improve the conductivity of the electrodes for edge collection. Peak power densities of 80 and 300 mW cm^{-2} were reported for hydrogen and air, and hydrogen and oxygen, respectively.

Using a cathode-supported approach borrowed from solid-oxide fuel cells, Frey *et al* built a fuel cell with sequential layer deposition [29]. The cathode catalyst was spray deposited directly on the substrate. Nafion was used as an electrolyte. However, instead of hot pressing the cathode into a bulk Nafion, a Nafion ionomer was spray deposited on the cathode. The anode catalyst and current collector are deposited on the spray deposited membrane. They achieve a respectable power density of approximately 20 mW cm^{-2} with 0.5 M methanol and a passive cathode. At the end of their paper they discuss the possibility of a serial strip cell system, which presages our design. They discuss possible current collectors and conclude that gold is the most appropriate current collector.

Table 1. Common fuel cell thicknesses.

Component	Unit thickness (μm)	Total thickness (μm)
Membrane	200	200
Catalyst layer	20	40
Gas diffusion layer (GDL)	200	400
Flow fields	3000	6 000
Gaskets	750	1 500
End plates	5000	10 000

In this paper, we describe the motivation, fabrication technique and performance of a low-cost micro fuel cell system. The first section describes the theoretical and economic motivation, setting the operating parameters for the cell. The second section describes the fabrication technique of the fuel cell system, and the final section presents and describes the results obtained.

2. Motivation

The design of micro fuel cells is significantly different from the design of automotive or stationary models. Micro fuel cells designs are dominated by volumetric energy density requirements. The incumbent technology, lithium ion batteries, has volumetric energy densities on the order of 300 W h l^{-1}. While wildly optimistic numbers for the energy density of a micro direct methanol fuel cell (μDMFC) have been put forward, the realistic numbers are much more modest. Operating at 20% efficiency, a μDMFC can achieve a fuel-based energy density of approximately 980 W h l^{-1} [10, 31]. A micro fuel cell could achieve this maximum energy density if it had zero volume. Obviously, no such fuel cell exists. Because every cubic centimeter not occupied by fuel will decrease the overall energy density of the system, it is critical to decrease the volume occupied by the fuel cell and balance of plant.

Micro fuel cells are not truly micro devices in the traditional MEMS sense, because the required surface area of the catalyst fixes the output power, which is independent of the fuel supply. Therefore, the surface area of the fuel cell can only be reduced by improvements in catalytic chemistry and electrode design. Any volumetric gains must be made by reducing the thickness of the fuel cell system. Table 1 illustrates some typical thicknesses for common fuel cell components.

As shown in table 1 the most significant reduction in volume can be achieved by reducing or eliminating the endplates, gaskets, flow fields and GDLs. Most researchers have concentrated on significantly reducing the thickness of the flow fields by moving from graphite to micromachined metal or silicon flow fields. Those with plate and frame designs have attempted to reduce the impact of the end plates by using thinner and more rigid materials. However, other researchers have attempted to remove the endplates entirely and create compressionless fuel cell architectures.

The second motivator to micro fuel cell design is cost. Like all other PEM fuel cell systems, micro fuel cells require expensive noble metal catalysts, and proprietary membranes. In addition, micro fuel cells have significant manufacturing barriers. Assembly of small pieces is a delicate process, and
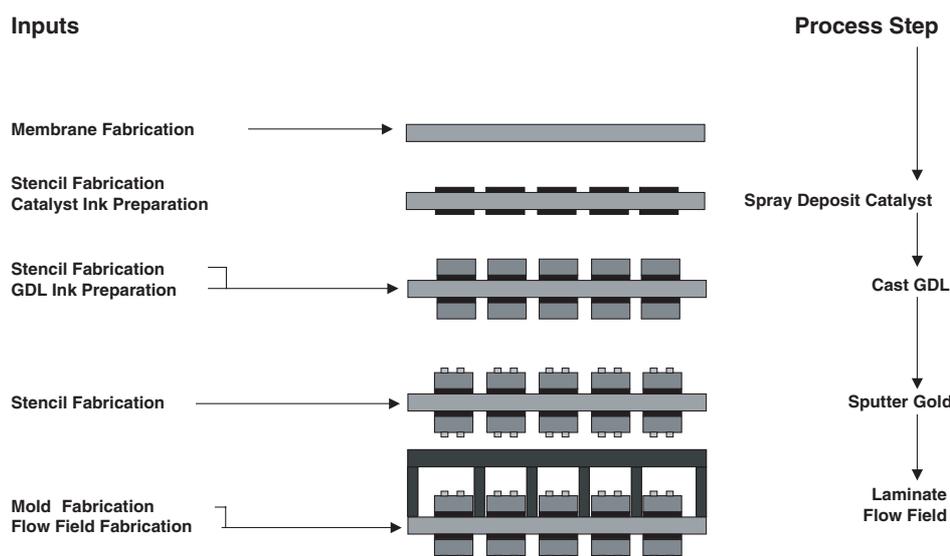
Inputs   **Process Step**

Figure 1. Fuel cell fabrication process.

mating flexible MEA components to rigid supports is a difficult process to automate.

Reliability was the final driver of our fuel cell design. We have not addressed the material specific reliability issues such as water management or cathode catalyst contamination. We have instead addressed the specific issues of reliability facing compressionless fuel cells: delamination, shock resistance and materials corrosion. Because micro fuel cells are targeted at the portable power market, they must be able to withstand the daily knocks experienced by commercial electronic devices. Additional padding to protect delicate components such as thin metal foils or silicon wafers reduces the overall power density. Compressionless designs like those of Kelley [6] and Muller [16] use the tension of the Nafion adhering to the flow fields to provide sealing and some local compression. However, repeated cycling of the membrane water content is likely to result in the delamination of the system. Furthermore, Muller's choice of nickel-coated brass as his flow field will result in corrosion. Our design attempts to overcome these design shortfalls while maintaining ease of manufacturing [30].

3. Fabrication

Our fuel cell fabrication technique is based on a sequence of thin- and thick-film depositions on a stable membrane substrate. Employing a dimensionally stable membrane as the substrate allows us to build the fuel cell in layers from the membrane out, without losing film integrity.

Figure 1 shows our fuel cell manufacturing process. The process begins with the fabrication of a dimensionally stable membrane. Bulk Nafion expands and deforms significantly when hydrated, and is thus an unsuitable substrate for thin-film depositions. A porous glass substrate loaded with Nafion provides a supporting matrix for the solid electrolyte. Next, the catalyst layer is sprayed through a stencil to create a sequence of segmented electrode regions. A castable GDL is deposited above the catalyst. Current collectors are sputtered through a stencil on the gas diffusion layer to perform bulk current collection. The membrane–catalyst–GDL–gold

assembly forms an MEA where bulk current collection occurs on the membrane, removing the need for compression to reduce current collector–MEA contact resistance. In parallel, a set of silicone channels is formed by casting a silicone over an SU-8/silicon mold. These channels are then attached to the MEA using a silicone-based adhesive.

3.1. Membrane preparation

Several authors have reported composite or supported membranes for use in fuel cell systems. While composite membranes generally have decreased conductivity, they are stronger, more durable and dimensionally stable than pure Nafion membranes [32, 39]. However, given the lack of commercially available supported membranes that met our requirements we were required to fabricate our own. After evaluating several substrates, we chose glass fiber substrates because they are inexpensive, hydrophilic, chemically inert and electrically insulating. The hydrophilicity makes these membranes easier to work with than PTFE-based membranes, simplifying the loading process.

The membrane is prepared by repeated immersion of a glass filter (Osmonics) in a concentrated Nafion solution then dried overnight at 80 °C. Two repetitions of this process were required to fabricate pinhole-free membranes. Membranes were prontonated in a 10% sulfuric acid for 1 h at 75 °C, then rinsed in DI water, and allowed to dry at room temperature before deposition of the catalyst layer. Nafion-free (unloaded) and completely loaded membranes are shown in figure 2.

The second image shows a typical cross-section that is well filled with Nafion and gas impermeable. However, point defects such as pinholes are difficult to detect with visual inspection if the defect follows a tortuous path through the membrane. There are some isolated voids in the right hand image. We cannot conclude that the voids were due to areas of low Nafion loading or an effect of the sectioning. Because the voids are isolated we can assume that they do not impact the impermeability of the membrane; however, if many voids were to align a tortuous pinhole could result.
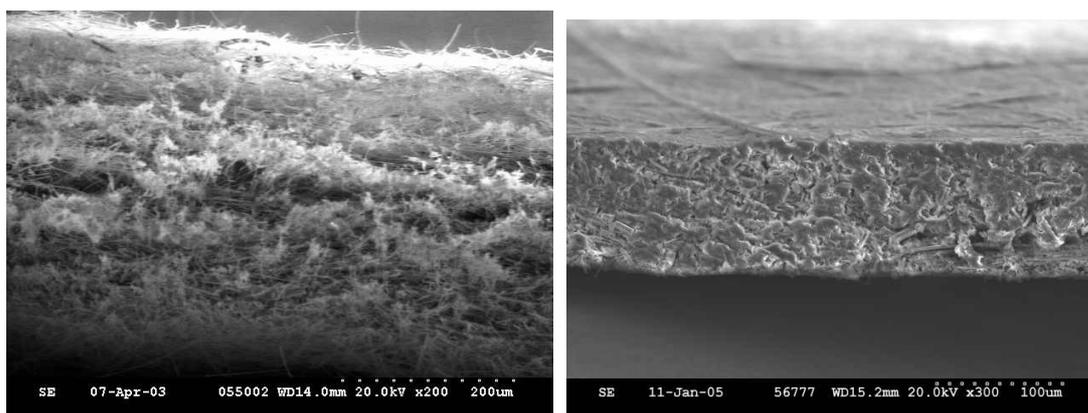
Figure 2. Raw glass fiber substrate (left) and Nafion loaded glass fiber substrate (right).

Table 2. Membrane characteristics.

Parameter	Value	Parameter	Value
Conductivity	40 mS cm^{-1}	Tensile strength	45 MPa
Surface deformation	0.37%	Elongation at yield	6.1%
Volume deformation	3.8%	Permeability (He)	0.69 μl min^{-1} cm^{-2}

Table 3. Castable GDL components.

Component	Mass ratio (%)
Carbon rods	55
XC-72A	7.5
SEBS	37.5

Table 2 contains the critical performance characteristics for our membrane. Conductivity was determined using ac impedance spectroscopy. Surface and volume deformation were determined using calipers and a micrometer to measure the dimensional change of square samples in completely hydrated and dehydrated states. Tensile strength and elongation were measured using a Test Resources 2000R pull-tester. To evaluate permeability, helium flow through a 9 cm^2 area of membrane with 4 psi back-pressure over a 10 min period. For the purpose of this paper, only the final results are relevant as they impact the fabrication and performance of the fuel cell. The parameters in table 1 are approximate, as variations in performance due to laboratory scale fabrication processes still exist.

Ionic conductivity was reduced with the volume fraction of the Nafion, but all the mechanical characteristics improved over bulk Nafion. In particular, the membrane resisted deformation from both applied loads and water content cycling. The stability of the membrane at low strains makes it particularly suited for reel-to-reel manufacturing techniques because it will not deform under stress or handling. The stability of the surface area under water cycling makes this membrane an excellent candidate for sequentially printed, compressionless fuel cells.

3.2. Catalyst ink preparation

The catalyst ink was prepared using standard methods. A 20 wt% platinum on XC-72A carbon from E-Tek was used as the solid phase of the ink. Butyl-acetate was added to the carbon to form a slurry. In a separate beaker, a colloidal Nafion solution was formed. A 5% Nafion solution in water and alcohols from Alfa-Aeser was mixed with isopropyl alcohol at a 1:1.5 ratio, then drop-wise butyl acetate at a total ratio

of approximately 1:1. Once the Nafion–isopropyl alcohol–butyl acetate solution changed from clear to light blue, the colloidal form had been achieved. The carbon–platinum–butyl acetate suspension and the Nafion colloidal solution were then combined in a high-speed mixer for 15 min.

3.3. Gas diffusion layer ink preparation

The gas diffusion layer (GDL) is created from a slurry of carbon rods and particles and a SEBS (polystyrene–block-(polyethylene-ran-butylene)–block-polystyrene) binder. Table 3 contains the relative mass ratios of the components. Unlike monolithic carbon paper electrodes, the slurry based GDL can be deposited through a stencil easing patternability.

The particle components are mixed in their dry form and the SEBS is dissolved and diluted in toluene. The current method of deposition, casting requires that the solids be a significant proportion of the total mass loading. The suspension should be the consistency of wet sand, which implies a toluene mass ratio of approximately 1:1.

3.4. Stencil preparation

Stencils were fabricated from 50 μm thick carbon steel shims (Lyon Industries). Carbon steel allows the attachment of the stencil to the substrate during depositions using a magnetic chuck. Carbon steel was sufficiently ferromagnetic to maintain adhesion and patternable using photolithography. Masks corresponding to the catalyst, GDL and current collector layers were designed in AutoCAD and exported as postScript files for direct acetate film printing.

A series of electrodes 2 mm wide and 2 cm in length were chosen for the electrodes. A set of strip cells could be wired in series or parallel depending on the requirements of the system. For sensor power, low current and high potential are required. The films were aligned under a microscope and attached with
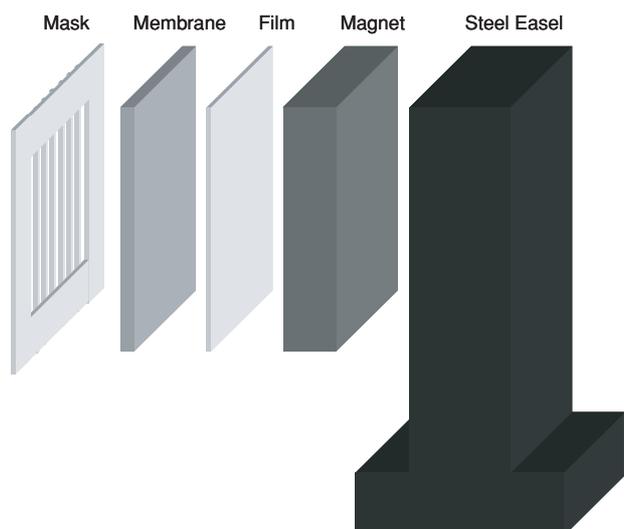
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Figure 3. Magnetic chuck assembly for catalyst deposition.

Figure 4. Application of GDL through stencil.

Figure 5. Test setup.

tape on one edge, forming a hinge. The metal foil was coated with photoresist (Shiply) on both sides and soft baked for 20 min. Both sides of the film were exposed under UV light for 90 s, baked for an additional 20 min, then developed. After developing, the steel films were etched in $FeCl_2$ (*aq*) until the pattern was clear.

Because steel etchents are isotropic, significant overetch occurred. Theoretically, the over etch should be twice the substrate thickness for a single sided etch, or equal to the thickness of the substrate for simultaneous etching from both sides. However, significant additional etching was required to completely clear the masks, resulting in additional lateral etching. The lateral overetch is exacerbated by the additional etching time required. In practice we found that an overetch of 2.5 times the thickness of the shim resulted from the additional etching time required.

3.5. Catalyst GDL and gold deposition

Deposition of the catalyst on the dimensionally stable membrane was accomplished by spray deposition. The membrane was placed on a magnetic chuck separated from the membrane by a layer of Parafilm. The ferromagnetic mask performs the duel role of holding the substrate in place and providing a stencil for deposition. Figure 3 shows the mask–magnet–easel assembly.

Once the mask and membrane are secured to the magnetic chuck, the entire assembly was placed against a steel easel to aid spraying. The catalyst ink was added to a spay gun and applied to the substrate. Spray was applied for approximately 2 s, then left to dry for approximately 10 s. The drying time allowed most of the solvent to be driven off, preventing the catalyst ink on the surface of the membrane from running. After 20 repetitions, the membrane was flipped, and front-back aligned on a light table with the stencil, attached to the magnetic chuck assembly and the process repeated on the opposite side. The catalyst layer was hot pressed at 1 US Ton for 3 min at 155 °C to facilitate the formation of a three-phase interface within the layer.

A variant of the magnetic chuck was used to attach the GDL-patterned stencil to the catalyzed membrane. The GDL
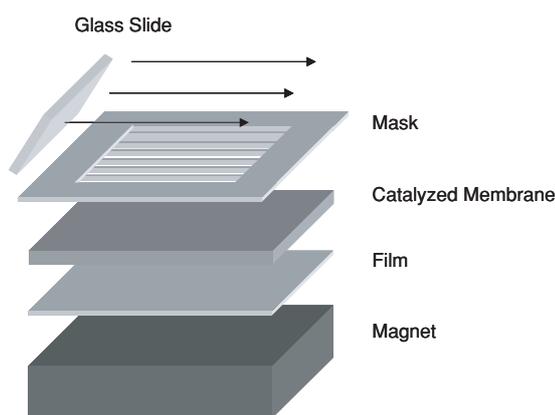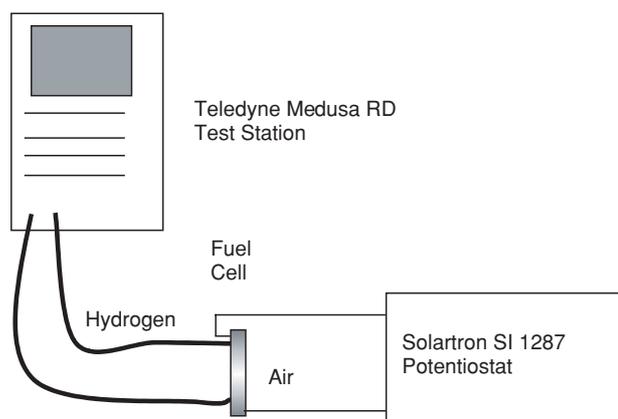
ink was poured onto the assembly and troweled off using a glass slide, resulting in a layer of GDL material with the same thickness as the stencil. A diagram of the process is shown in figure 4.

Following application of the GDL, the MEA was dried at 80 °C for 2 h to drive off the solvent. The process was then repeated on the opposite face, and the membrane dried at 80 °C overnight to ensure no solvent remained trapped in any of the micro pores.

The gold was deposited using sputter deposition through a stencil prepared in the same manner as the catalyst stencil. While stencil-based patterning reduces the accuracy of deposition, the MEA was not exposed to organic solvents, which can displace the water within and warp the membrane. The gold pattern was a series of four 200 μm strips deposited on top of each GDL electrode. The stencils are aligned by hand under a microscope and transferred to a magnetic chuck prior to sputtering. A 300 nm thick layer of gold was typically deposited.

3.6. Channel and mold preparation

Our flow fields can be made from an insulating material because bulk current collection was performed on the MEA. The channels are formed using a replica molding technique. The molds are fabricated from photo-patternable epoxy (SU-8 from MicroChem Corp.) and silicon.
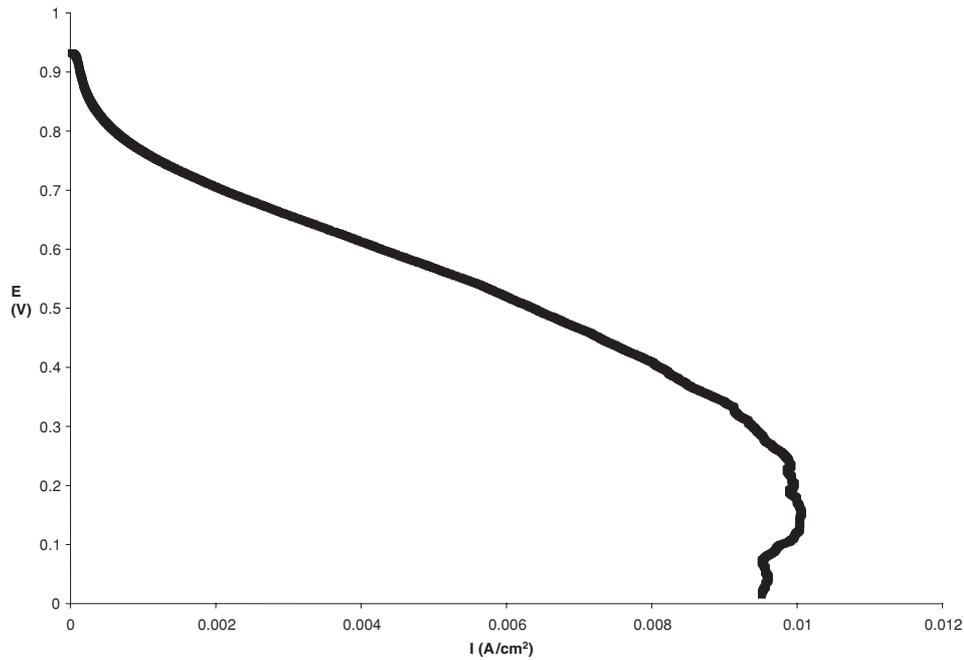
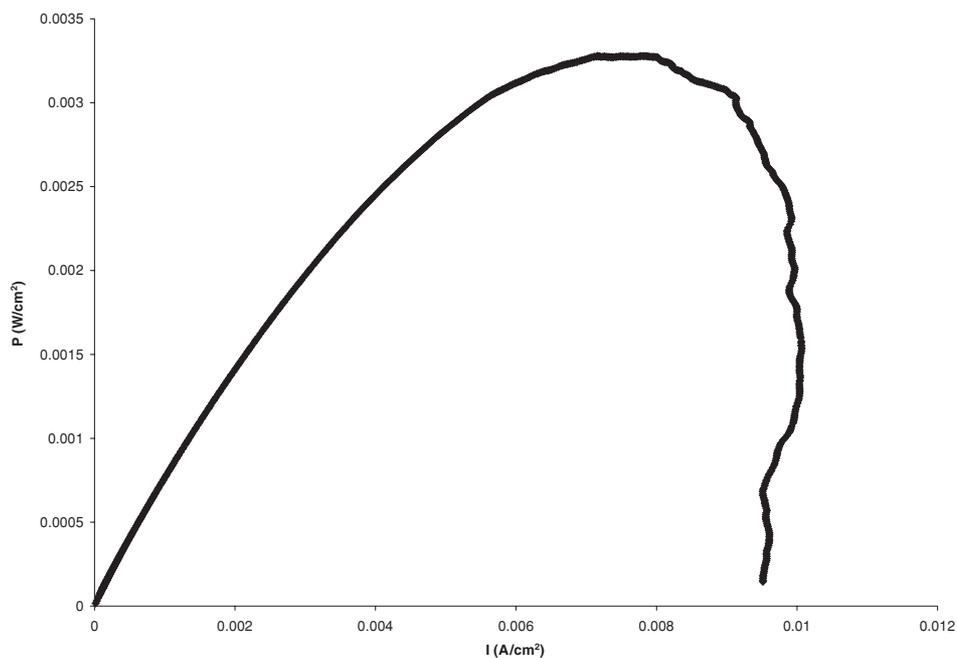**Figure 6.** Polarization data.

Figure 7. Power data.

The SU-8 was spun on a flat substrate such as a silicon wafer or glass plate at ∼700 rpm for 30 s. After a short period where the film was allowed to relax, it was placed in an oven at 100 °C for approximately 2 h. The film was then exposed to UV light three consecutive times for 45 s each through an emulsion mask with the desired pattern and baked again at 100 °C for 15 min. The film was developed in SU-8 developer at room temperature with gentle agitation. The developed SU-8 film was then silanized according to Schueller *et al* [40] to passivate the surface.

The flow fields are cast directly onto the mold using Dow Corning Sylgard 182 mold making silicone rubber. The catalyst and compound are mixed using the suggested process of the manufacturer, using a 20 to 1 ratio. Gentle mixing was required to avoid embedding bubbles in the mixture. The mixture was sonicated for 3 min after mixing to remove bubbles. The mixture was poured over the mold approximately 2 mm deep on a clean level surface. After 12 h of curing time, the cast flow fields could be removed by hand, and any excess rubber cut away.

Sealing the flow fields to the membrane was accomplished using standard silicone rubber adhesive. The adhesive can be painted directly onto the flow fields, or can be spread in a thin layer on a flat substrate, and flow fields rolled over the film like a stamp. Once the adhesive has been applied, the flow fields are affixed on the membrane by applying modest pressure.

4. Results

The fuel cell was tested on a Teledyne Medusa RD test station, which provided a constant and controlled humidified hydrogen gas stream 100 ml min^{-1} at 30 °C. Because the station's load bank does not have sufficient resolution at lower power densities, an external load and measurement apparatus was used, a Solartron SI 1287 potentiostat, which performed load stepping and potential and current measurements. The testing setup is diagramed in figure 5.

Figures 6 and 7 show the measured performance. The cell achieves a peak power of approximately 3.2 mW cm^{-2} and a peak current density of 10 mA cm^{-2}. The most significant characteristic of this curve was the Ohmic resistance. The potential of the system descends much faster than in a standard compressed fuel cell. This degradation was primarily due to the resistance of the uncompressed catalyst layer, and the poor conductivity of the GDL. Because current is collected laterally, the conductivity of the GDL/gold current collector must have a conductivity of at least 500 S m^{-1}. In this example the slope of the Ohmic region is 47.8 Ω cm^{-2}. A typical bipolar fuel cell system will have an apparent Ohmic resistance of 0.1–0.5 Ω cm^{-2}. Despite the shortcomings in comparison to standard fuel cell configurations, this performance matches favorably with some other compressionless fuel cell designs reported in the literature.

5. Conclusions

We have created an uncompressed micro fuel cell that is simple and inexpensive to manufacture. We have decreased the thickness of the fuel cell in an attempt to address the needs of portable applications. Because all the current collection was performed on the membrane, the flow channels can be formed from an insulating material. Our fuel cell showed respectable performance when compared to other compressionless fuel cell designs, but exhibited a large Ohmic resistance when compared to traditional fuel cell designs. The high Ohmic resistance was primarily due to contact resistance within the particle-based catalyst and GDL layers. Future work will address the reproducibility of the fabrication process and new methods to reduce the resistance of the GDL and current collection layers.

Acknowledgments

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