Size does matter
The pros and cons of miniaturization

Sangkyun Kang, Sang-Joon J. Lee, Fritz B. Prinz

As paradoxical as it might sound, miniaturization is playing an ever-bigger role in our lives. PCs, phones, PDAs and consumer electronics all continue to shrink in size. And they have become faster: sub-micron manufacturing has brought us operating frequencies unimagined just a few years ago. Now miniaturization is moving into other product areas, such as turbo-machinery and fuel cells. Here, however, besides promising significant performance benefits, it can also exact a price – for example, less precision or increased frictional losses.

Recent years have seen ideas from the miniature world being taken up enthusiastically by other disciplines. A good example can be found in the field of MEMS (Micro-Electronic Mechanical Systems). These systems draw on existing micro-electronic fabrication techniques to create miniature sensors (eg, accelerometers), and micro-actuators (valves, mirror arrays). One great advantage of MEMS is that they can be arranged relatively easily in parallel to improve product reliability. However, there is a trade-off, too: as size goes down, precision loss and frictional losses go up.

Against such a background, the implications of MEMS manufacture are obviously worth a closer look. Two areas in which MEMS and other precision fabrication techniques are already making their mark and which demonstrate these implications well are micro-engines and micro-fuel-cells.

Scaling implications for turbomachinery

A mechanical system can be described by its mass m, distance d, device size l, and time t. In order to compare the behavior of large systems with their smaller-scale counterparts some assumptions have to be made. For example, it is assumed that the potential energy density, $U(d,d)$, and indeed the material density, ρ, remains constant. Also, it is assumed that any change in feature size l, which is related to the mass as $m = l^3$, is also accompanied by a change in the distance parameter d.

Having set out these assumptions, a look can now be taken at how downsizing affects a turbine.

The net amount of energy density transferred to the shaft of a turbomachine under steady-state conditions, disregarding gravity and entropic losses, can be written as a form of the energy (kinetic + potential) equation:

$$\frac{1}{2}\rho\left(v_2^2 - v_1^2\right) + p_2 - p_1 = E / V$$

$v_{1,2}$ stands for the velocity of fluid at the machine inlet and outlet. The potential energy density term $p_2 - p_1$ does not include any parameter that depends on the size of the turbomachine, which leads to the important result that *the length and time (period) are proportional.* For example, if a gas turbine is made smaller (shorter length), it will spin faster (shorter period) assuming the energy density of the driving gas is the same. While this analysis is largely simplified (it ignores loss and efficiency), useful insights regarding size and power density can be derived, as shown below.

The dynamic behavior of turbomachines can be described by mathematical relations between the rotor diameter D and the rotating speed N. Dimensional analysis [1] gives the generated torque of a turbine as

$$L = c_1 \rho D^5 N^2$$

Also the generated power is defined as $P = L\,N = c_1\,\rho\,D^5\,N^3$. Here, the power density in terms of volume is defined as

$$p = \frac{P}{V} = c_2\frac{D^5N^3}{D^3} = c_2D^2N^3$$

This shows that the power density of a turbomachine depends on D and N. Keeping the surface speed constant and using the proportional relationship between length and time as argued above, $D \times N$ will be constant. Accordingly, the power density becomes,

$$p = c_2D^2N^3 = c_2(D \times N)^3\frac{1}{D} = c_2(c_3)^3\frac{1}{D} = c_4\frac{1}{D}$$

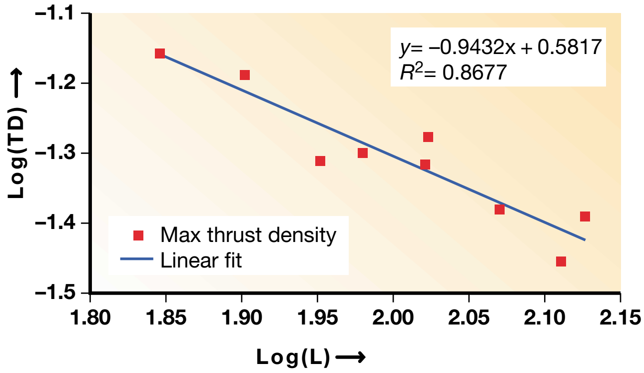
This indicates that the power density of turbomachinery increases as its size goes down. A similar argument is possible for the thrust-generating gas turbine engines. 1 [2] shows the relationship between thrust density and length scale for Pratt and Whitney commercial jet engines. The slope of the fitted line, –0.94, compares well with the predicted value of –1.

Further, it can be shown that as the maximum linear speed of a rotor blade tip is determined by the strength of the rotor material, keeping constant surface speeds for turbomachinery at different size scales is a good idea. The maximum value of $D \times N$ is then constant for two rotors of different size but of same shape and material. The constant rotor surface speed implies the same flow speed in turbomachinery. The blade tip speeds are, again, similar for the turbomachines with different diameters.

Reliability and massively parallel mechanical systems

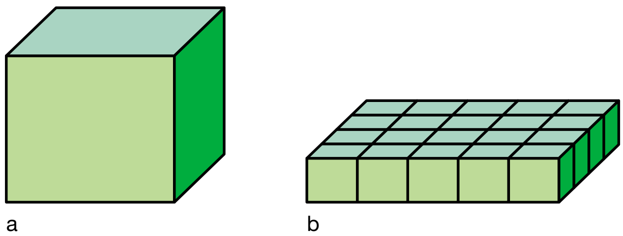
The increased power density of small mechanical systems leads to the possibility of massively parallel mechanical systems (MPMS). These have significant size and reliability advantages. For example, one big engine can be replaced by a multiple of smaller engines. Since the power density of a small engine is higher than that of a larger machine, the former can generate the same power with a smaller volume 2. 3 compares the failure probability of one big engine and the redundant system illustrated in 2.

1 Relationship between thrust density (TD) and length (L) of Pratt and Whitney commercial jet engines



2 Single engine system (a) and redundant system (b) with 20 small engines

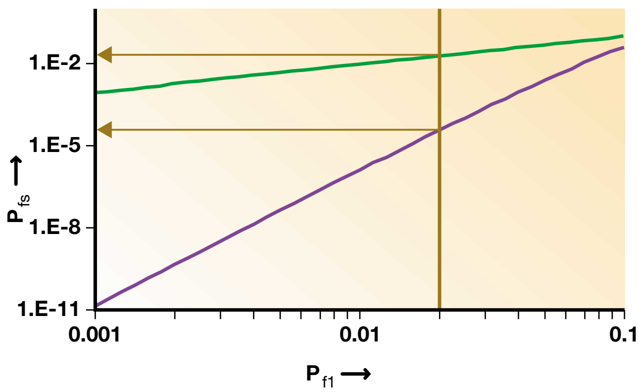
One big engine is replaced by engines 4 times smaller. Since the power density of the smaller engines will be 4 times higher, the massively parallel system will generate the same power with a quarter of the volume. The saved space is used by 4 more small engines, added to improve the reliability of the system.



3 Failure probability comparison of a system with one big engine (green line) and 20 small engines (purple line). Assuming the failure probability of each engine is 2×10^{-2}, the failure probability is 2×10^{-2} for one engine but 3.8×10^{-5} for the redundant system.

P_{f1} *Failure probability of each engine*

P_{fs} *Failure probability of 20-engine system*

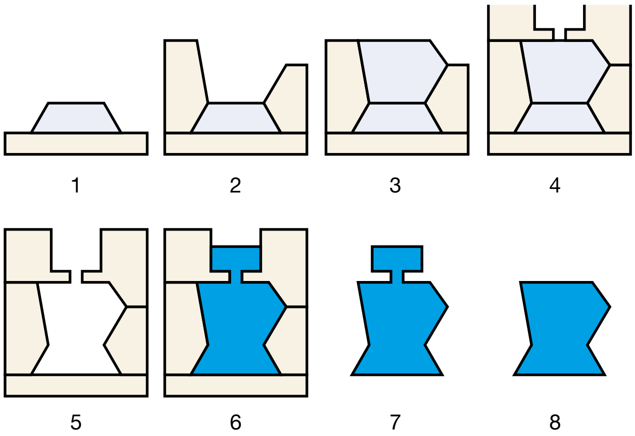


4 Mold SDM procedures

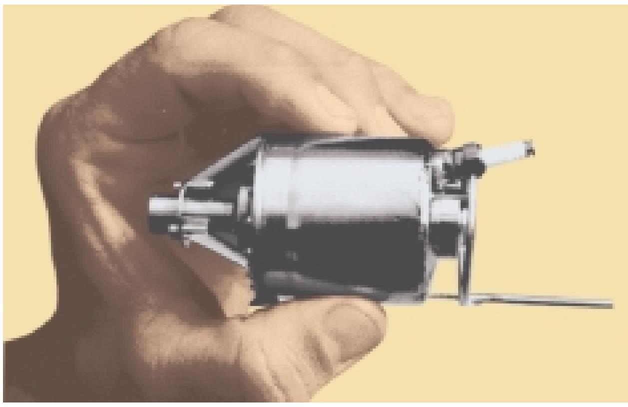
Beige *Mold material*

Gray *Support material*

Blue *Part material*



5 M-DOT micro-gas-turbine engine



Drawbacks of downscaled mechanical systems

Traditional manufacturing processes, such as milling, turning and molding, can achieve relative accuracies of the order of 10^{-4} to 10^{-6}. Relative accuracy is defined as the manufacturing process tolerance Δl divided by the characteristic part dimension l. This will clearly decrease as part dimensions shrink.

Modern micro-fabrication methods like reactive ion etching (RIE) achieve a $\Delta l/l$ of only 10^{-2} to 10^{-4} and manipulation of individual atoms or molecules with AFM probes may achieve values for $\Delta l/l$ of the order of $0.5 - 10^{-2}$ at best. The lower relative accuracy at smaller dimensions is of particular concern in mechanical systems where parts may move relative to each other. 'Rough' surfaces may cause increased friction and heat generation, leading to reduced efficiency and a shorter lifetime for small-scale systems.

Mold shape deposition manufacturing of turbomachinery

Mold Shape Deposition Manufacturing (Mold SDM) 4 is a two-stage manufacturing process that can be used to build ceramic, metal and polymer parts. A fugitive wax mold is first built using an additive-subtractive layered manufacturing process (steps 1 to 4). A variety of castable materials, including ceramic and metal gel-casting slurries as well as castable thermoset polymers, can then be cast into the mold to produce a part (step 6). After removal of the mold (step 7), finishing operations, such as casting feature removal, are performed, leaving the finished part in step 8. Sintering can be performed after either step 7 or 8 [4].

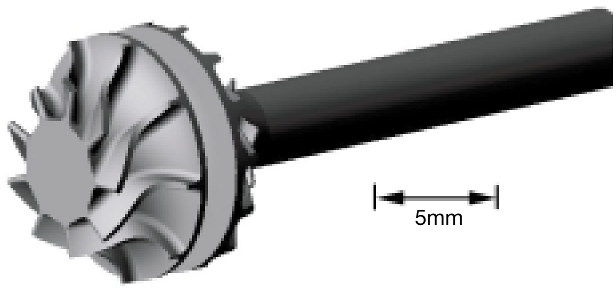
Mold SDM has several advantages over other manufacturing processes. As a layered manufacturing process it can be used to build complex shapes, and unlike most of these – purely additive – processes, it is additive-subtractive. The subtraction step, performed using CNC milling, enables the creation of smooth, accurate geometries. Mold SDM is also capable of building parts from a wide range of castable materials.

For the manufacture of complex ceramic parts, Mold SDM has two key advantages over other layered manufacturing processes. First, all surfaces are either machined or replicated from machined surfaces. This results in smooth, accurate surfaces without any stair step effect. Second, the part material is cast monolithically. There are therefore no potential defect-promoting layer boundaries in the finished part. These advantages are particularly important for flaw-sensitive materials where surface roughness and internal defects can significantly reduce the mechanical strength.

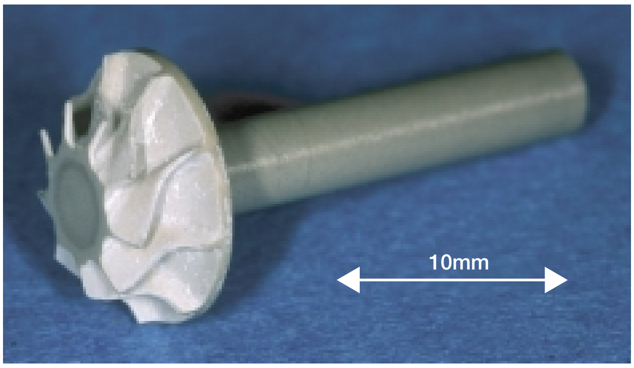
Mold SDM and the miniature turbine

5 shows the metal micro-gas-turbine engine designed and fabricated by M-DOT Aerospace (Arizona, USA). Better thrust/weight ratio and efficiency can be achieved by replacing

6 CAD model of the silicon nitride rotor group of the micro-gas-turbine engine. Turbine diameter: 12 mm. Minimum blade tip thickness: 220 μm. The part is designed to run at 800,000 rpm.



7 The sintered micro-turbine used for the spin test



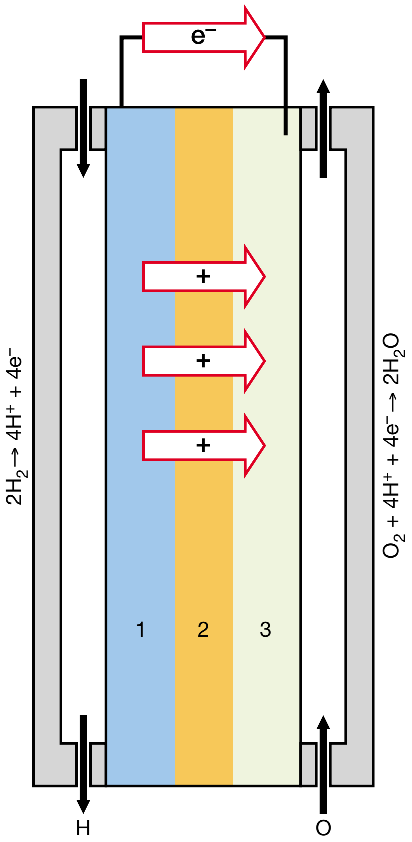
the metal parts by ceramic parts due to the low density and high temperature properties of ceramic material. The next version of this engine 6 will have the rotor shaft, compressor and turbine combined in a monolithic silicon nitride part.

The surface quality of the rotor group is important because the strength of ceramic parts is highly dependent on the surface condition. It must also be noted that the rotor geometry does not allow post-processing, such as grinding, due to its complex shape. A manufacturing process that can produce a ceramic part of complex shape with good surface finish is required to build the micro-gas-turbine engine parts.

Recently, silicon nitride miniature turbines 7 have been built using Mold SDM and spin tested with air at room temperature. The test results show that the micro-turbine spun up to 460,000 rpm. Considering that the turbine was designed for high-temperature gas, which has a higher speed of sound and more internal energy, the result seems quite favorable [4].

Scaling implications for fuel cells

A fuel cell is an electrochemical device that produces electrical current directly from chemical reactions. A basic assembly consists of an ion-conducting electrolyte membrane between two electrodes, backed by fuel and oxidant flow distributors 8. A catalyst on one electrode promotes the separation of ions and electrons on the fuel side. Only the ions conduct through the electrolyte, and recombine with electrons on the



8 Basic fuel cell

1 *Anode*

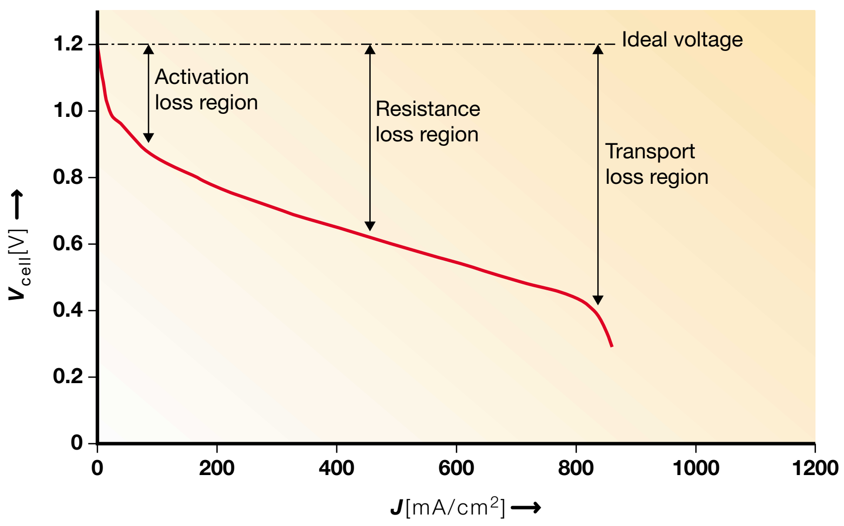
2 *Membrane*

3 *Cathode*

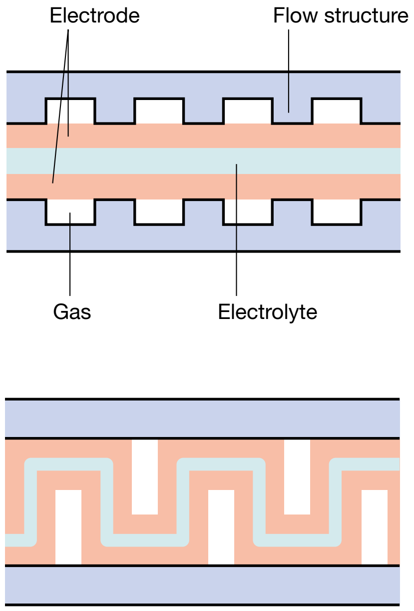
9 Typical I-V performance curve of a fuel cell

V_{cell} *Cell voltage*

J *Current density*



10 Planar cell (top) versus 3-D configuration



oxidant side. The electrons conduct through an external circuit, and thus supply electrical power.

In an ideal case, the fuel cell (or stack of cells) would provide as much current as the external load requires, and the voltage would remain constant. However, in reality there are voltage losses that increase with a higher current load, as the typical current-voltage curve in **9** shows.

A high-performance fuel cell is one that offers high peak-power and high current density with minimum loss of voltage. The losses arise mainly from activation limitations at low current density, ohmic losses at medium current density, and reactant transport limitations at high current density.

The fundamental point of interest for fuel cell miniaturization is its effect on the overall power density of the device. There are two basic approaches to examining the scaling implications for fuel cells, assuming that maximum power density is the primary criterion.

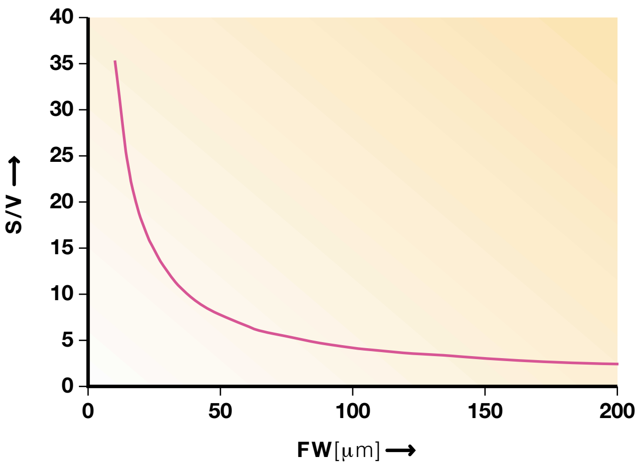
One immediate question is whether miniaturization can geometrically benefit power density in terms of watts per unit area. Here, the main focus is on the surface-to-volume ratio for very small fuel cells.

The second, but equally important, consideration is the extent to which smaller dimensions may offer fundamental benefits in terms of current-voltage performance, by affecting factors such as kinetics, fluid mechanics and heat transfer. The following examples explore some specific cases.

Power density and geometric considerations

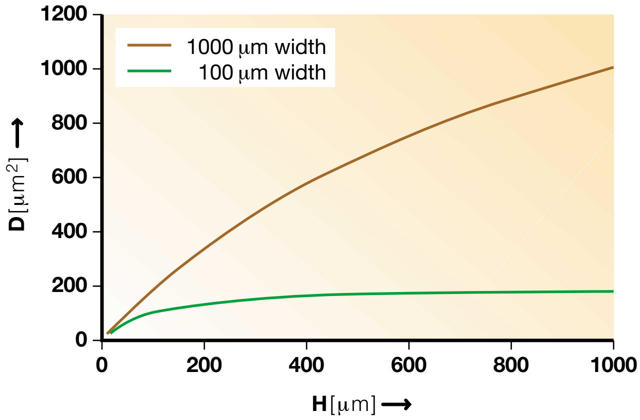
Most fuel cells have flat, microporous electrodes separated by an electrolyte layer. This design is particularly well suited for continuous fabrication. Some solid oxide fuel cell designs, however, have cylindrical as well as corrugated shapes, due mainly to manufacturing and operational considerations [5].

The principle of non-planar interface layers can be extended to provide a dramatic improvement in surface-to-volume ratio, especially if micro-fabricated dimensions are attainable. **10** contrasts a conventional planar design with a three-dimensional interface. The 3-D design offers extra area at the electrolyte interface by providing vertical surfaces. These meso-scale features, of the order of 10 or 100 µm, complement the micro-porous and nano-porous surfaces that are already present in the gas diffusion electrodes themselves.



11 **Normalized surface-to-volume ratio (S/V) versus feature width (FW) for a corrugated fuel cell**

Electrolyte thickness 60 µm, electrode thickness 80 µm, flow backing 500 µm. The figure shows that for very small feature sizes, a dramatic improvement in surface-to-volume ratio is achieved with corrugated features. (The normalized surface-to-volume ratio is defined here as the surface-to-volume value of a textured cell divided by that of a planar counterpart.)



12 **Hydraulic diameter (D) versus channel height (H) for 2 channel widths.**

A larger hydraulic diameter corresponds to the desirable condition of lower pressure loss, making the wider channel (1000 µm) preferable in this example. Interestingly, the scaling relationships dictate that D is relatively insensitive to H once a width penalty (100 µm) has been imposed.

Adding a height component may increase the overall volume of the device compared with a strictly planar design. However, increasing the height by texturing increases the volume by only one finite amount, whereas narrowing the feature width continues to increase the surface area with no further impact on volume.

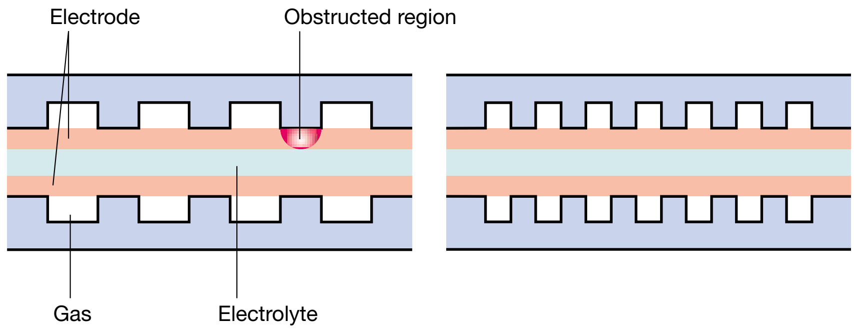
The extent to which area can be enhanced is restricted only by the minimum feature width required for functionality and manufacturability. Accordingly, there will be limiting design rules and critical dimensions, as exist for integrated circuit fabrication. Typical dimensions already common to polymer electrolyte fuel cells do offer significant opportunity for improvement. Critical dimensions are expected to decrease as miniature fuel cell technologies develop, and this will allow rapid improvement reminiscent of the successful shrinking of integrated circuits. **11** shows a case example using parameters already achievable with present technology.

Power density and performance considerations

Flow resistance is an important miniaturization parameter. In flow channels, pressure loss is inversely proportional to the 'hydraulic diameter', which varies with channel size **12**.

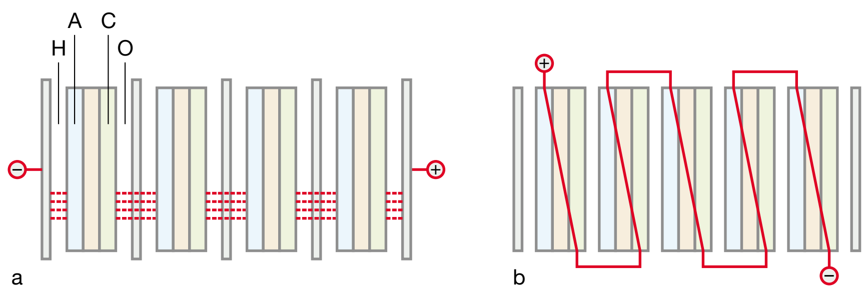
A second important parameter is gas diffusion. In fuel cells the transport of reactants to the electrolyte interface is driven by diffusion of gas molecules through porous electrodes. One particular advantage of micro-machined flow structures is the

13 Micro-machining allows obstructed regions at shoulder locations to be reduced by making the footprint smaller (right).



14 Bipolar (a) versus monopolar (b) fuel cell stack configurations

A *Anode*
C *Cathode*
H *Hydrogen*
O *Oxygen*



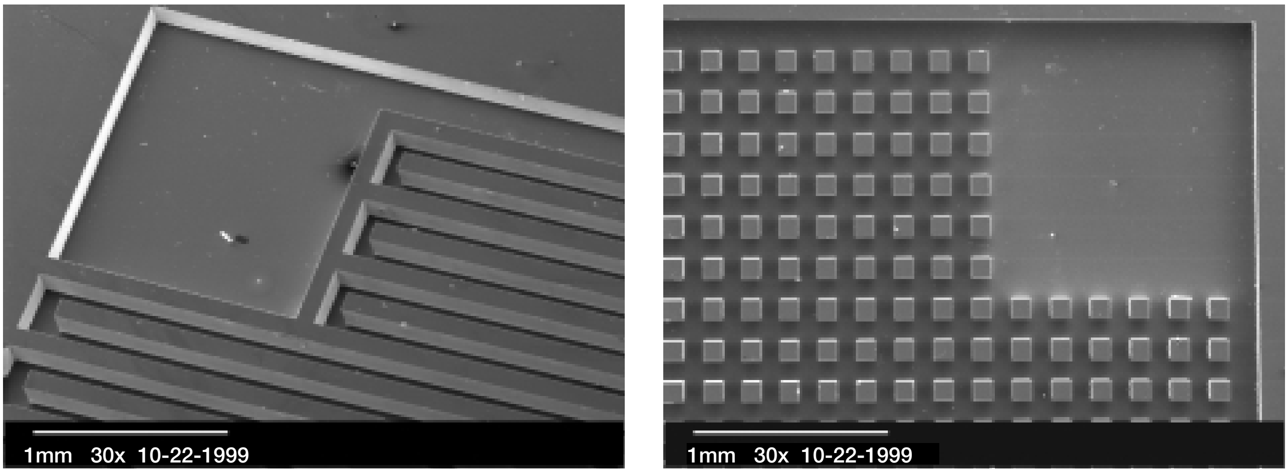
fact that obstructed regions at shoulder locations can be reduced. This enhances the overall gas diffusion performance across the porous electrodes. 13 shows how reduced channel size can offer the same electrical contact area (50% in this case) with smaller obstructed regions and more uniformly distributed mechanical support.

A further significant property of a fuel cell is its electrical resistance. Low electrical resistance is desirable for high efficiency in fuel cell energy conversion. The electrical resistance R is proportional to the travel length L and inversely proportional to the cross-sectional area A.

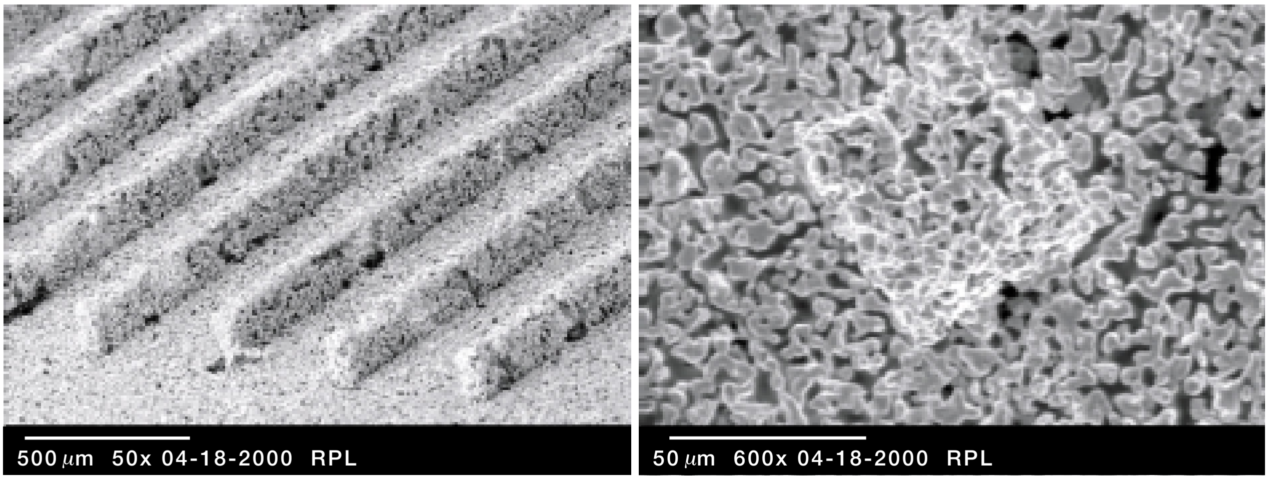
The resistivity of a material does not generally depend on size unless the dimensions begin to approach atomic scale. A benefit of miniature design is that circuit interconnections between series cells are generally shorter than their large-scale counterparts. However, a size reduction uniform in all dimensions generally results in higher electrical resistance, because the resistance is inversely proportional to a length-squared term.

Miniaturization does offer a subtle benefit related to shorter conduction paths. Fuel cells have two common configurations for series connection, monopolar and bipolar 14. The bipolar construction is almost universally adopted for automotive and larger-scale applications because of its simple construction. However, the monopolar layout is fundamentally more compact, because one fuel chamber

15 Samples of flow structures in silicon with 100 µm channel features. Channel sizes ranging from 200 µm down to 50 µm have been produced on 1 cm^2 cells, and typically sixteen or more cells are fabricated simultaneously on each 100 mm silicon wafer.



16 Micro-porous electrodes produced by metal gel-casting



services two anodes, and one oxidant chamber services two cathodes.

The monopolar design has a disadvantage for large-scale systems as the electrical current must flow laterally across electrodes; however, in a miniature system these distances are much shorter. Hence, a smaller system offers the option of more compact design through use of the monopolar stacking arrangement.

Fuel cell fabrication

The so-called deep silicon etching process 15 permits high geometric complexity at near-zero marginal cost, which is in stark contrast to conventional manufacturing processes like machining.

Fundamental requirements for the electrode material include high surface area for catalyst support, high electrical conductivity, and uniform gas diffusion. The concept of a meso-scopic, three-dimensional interface, however, adds the not-so-trivial requirement of texture definition. Several candidate approaches have been investigated to achieve this level of fabrication control. Initial studies included plasma spraying, co-electroplating with a sacrificial material, and malleable paste formulations. Porosity control proved to be the greatest challenge in most cases.

A novel technique called micro-mold metal gel-casting has been adapted to achieve patterned, micro-porous feature definition previously unattainable with other methods. In this technique, metallic powder is dispersed into a solution to form a gel, which is then cast into a predefined mold. After debinding, the metal green part is sintered under conditions which are optimized for porosity and bulk strength. Etched silicon molds as well as other photo-lithography-based molds were used to create micro-porous silver electrodes with texture features of the order of 100 µm, as shown in 16. Features as fine as 25 µm have been successfully cast from silicon molds.

The ability to arbitrarily pattern electrodes with controlled porosity not only benefits 3-D interface design, but also provides greater opportunity for integrated, functionally optimized flow distribution. This design freedom allows extended solutions that address critical issues such as flow resistance and diffusion uniformity.

Going from theory to practice

Although considerable progress has been made on all fronts, much work remains to be done in the empirical area. Here, advances in manufacturing technologies will play a critical role in the construction of prototypes, for example of turbine and fuel cell components, for functional testing.

Among other ongoing efforts, ABB is collaborating with Stanford University to exploit the benefits of the downscaling knowledge accumulated to date and to study ways of applying it to industrial sensing.

Authors

Sangkyun Kang
Rapid Prototyping Laboratory
Stanford, CA 94305-3030, USA
kangsk@stanford.edu

Sang-Joon John Lee
PO Box 19760
Stanford, CA 94309, USA
sang-joon.lee@stanford.edu

Fritz B. Prinz
Rapid Prototyping Laboratory
Stanford, CA 94305-3030, USA
fbp@cdr.stanford.edu

ABB and Stanford University collaborate closely in a number of areas. In this ‘guest’ article, Prof. Prinz, R. H. Adams Professor of Engineering in the Departments of Mechanical Engineering and Materials Science and Engineering, and his colleagues report on new downscaled manufacturing techniques. These are having an impact on ABB’s product development; joint projects have been started to exploit the benefits of Stanford technologies in the field of industrial sensing.

References

[1] **G. T. Casanady:** Theory of Turbomachines. McGraw Hill, New York, 1965.
[2] http://www.pratt-whitney.com/engines/commercial.html
[3] **A. G. Cooper, et al:** Fabrication of structural ceramic parts using Mold SDM. Proceedings of the American Ceramics Society meeting, Cocoa Beach, Florida, USA, Jan 2000.
[4] **S. Kang, et al:** Application of the Mold SDM process to the fabrication of ceramic parts for a micro gas turbine engine. Proceedings Ceramic Materials and Components for Engines, edited by J.G. Heinrich, Germany, June 2000.
[5] **N. Q. Minh:** Ceramic Fuel Cells. Journal of the American Ceramic Society. 76, 3 (1993).