A Microfabricated Direct Methanol Fuel Cell with Integrated Electroosmotic Pump

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Miniature direct methanol fuel cells (DMFCs) offer the promise of higher energy densities for portable electronic devices [1]. Overall system size, cost, and longevity of both fuel cell stack and balance of plant, present significant barriers to widespread proliferation. Electroosmotic (EO) pumps are a robust alternative to conventional liquid pumps because they have no moving parts, produce flow rates on the order of several ml/min. [2-4], and can be microfabricated in silicon using standard techniques. This paper reports the design and performance quantification of a miniature DMFC with a micromachined silicon EO pump integrated into the fuel cell anode for methanol fuel delivery and CO_2 gas control.

Recent studies indicate that both miniature DMFCs and EO pumps can be fabricated from silicon substrates using standard MEMS fabrication techniques [1-2]. Previous work on miniature DMFCs has focused on fabrication of fluid flow channels for reactants and products and the integration of these structures with a membrane electrode assembly (MEA). Very recently, some of us have applied EO pumps to the cathode of direct hydrogen fuel cells for water management [5], but EO pumps have not been demonstrated for integrated fuel delivery. This paper will illustrate the efficacy of using micromachined EO pumps for methanol delivery. Experimental studies detailing the pressure and methanol flow rate capacity for the microfabricated EO pumps and polarization data for the combined DMFC/EO pump system will be presented.

The EO pump integrated into the cell anode consists of 5 μm by 360 μm slots etched into the 150 μm thick device layer of a silicon on oxide (SOI, 0.5 μm buried oxide layer). The design pumps methanol directly into 400 μm anode flow channels on the 300 μm thick handle side of the wafer. Integration of the EO pump and the flow channels in this manner eliminates the need for a seal between the pump and fuel cell anode and reduces the number of components and processing steps. Digital and SEM images of a sample device are shown in Figure 1 and a schematic of the fabrication process is shown in Figure 2.

The active area for the DMFC is 2 cm^2, which requires 1M methanol flow rates of order 0.5 ml/min [1]. The current DMFC system uses a 4M methanol solution to reduce required flow rate and increase volumetric power density of the system. Preliminary calibration of the EO pump was conducted with deionized water at applied voltages ranging from 50 to 100 V (Figure 3). A maximum flow rate of 10.4 ml/min for structures having 8% porosity was realized at 100 V. Assuming electroosmotic flow is modeled as Stokes flow with a slip boundary condition, the theoretical maximum pump flow rate is,

$$Q_{\max,theor} = -\left(\psi A_{tot}\right)\frac{2\varepsilon\zeta Eh}{\mu}, \quad [1]$$

Where ψ is porosity, ζ is zeta potential, E is electric field, h is channel half height, ε is permittivity, and μ is viscosity. Theoretical flow rate versus voltage is plotted in Figure 3. Full quantification of EO pump pressures and flow rate using various methanol/water mixers will be presented along with the quantification of the fuel cell/EO pump system performance.

The performance of our free convection DMFC with integrated EO pump gives a maximum power density of 17.8 mW/cm^2 at room temperature using a 4M methanol solution. Our results are comparable to previous reports [1] for DMFCs of similar size. DMFC polarization and power density curves are shown in Figure 3 for the complete fuel cell/EO pump system at room temperature. Additional studies of the dependence of the polarization curves on methanol fuel concentration and applied pump potential will be conducted.

Word count: 590

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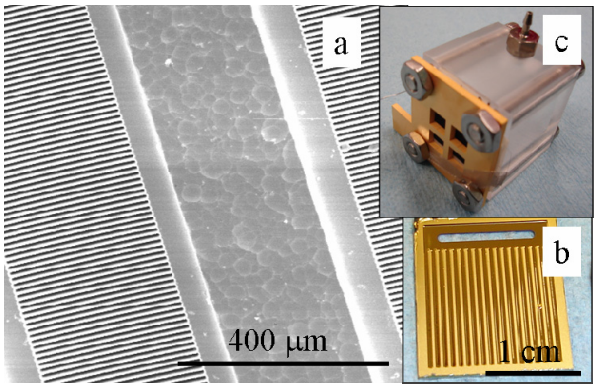

Figure 1: SEM (a) and digital image (b) of the top view (handle side) of our integrated EO pump/DMFC anode structure and the full DMFC assembly (c). The SEM image is a top view into the flow channels showing the 5 µm wide EO pump slots etched into the bottom of the 400 µm wide anode flow channels. The pump slots deliver methanol perpendicular to the plane, out of the page, and into the anode channels. The anode channels (b) allow methanol to flow through the plane and react along the MEA. A 1 mm wide slot at the edge of the structure recirculates the methanol back to the reservoir and advects generated CO_2 out of the system.

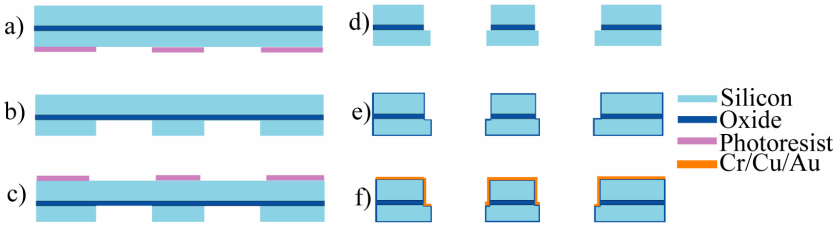

Figure 2: Integrated electroosmotic pump and anode flow channel fabrication process. EO pump trenches (b) and methanol flow channels (d) are created using DRIE. The buried oxide layer is opened with a wet etch and oxide is grown (e) to obtain the necessary surface properties [2]. A chromium/copper/gold layer is evaporated to create an electrical connection with the MEA and serves as the EO pump cathode.

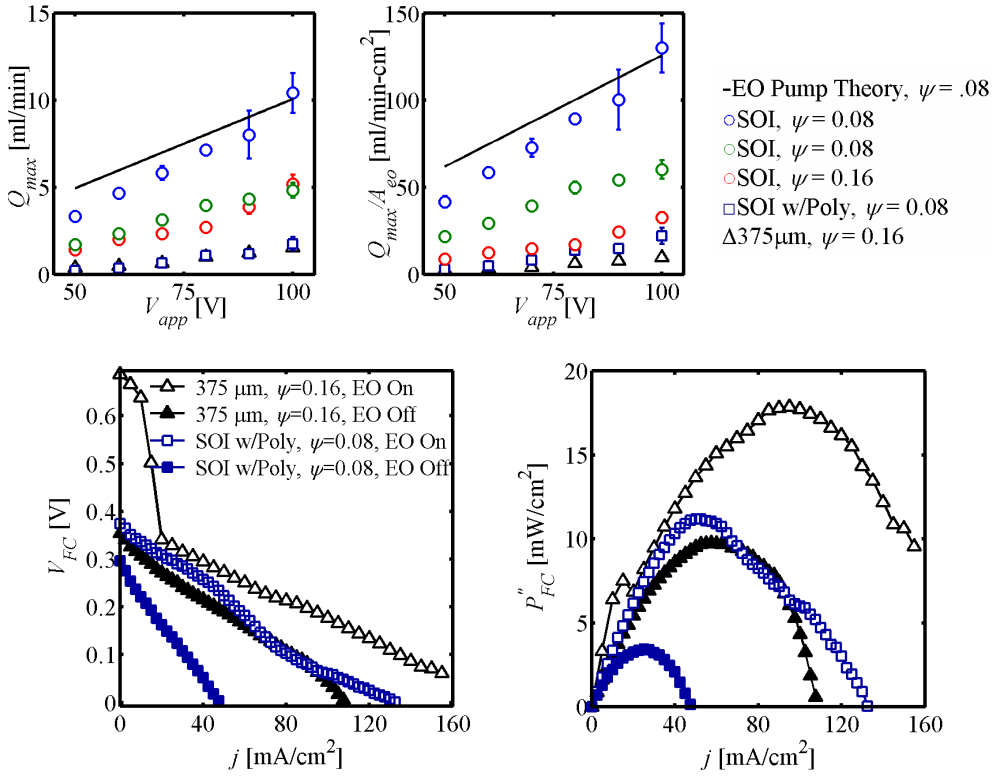

Figure 3: Absolute and flow rates scaled by area (top) are shown for varius fabricated EO pumps with different EO pump thicknesses. ψ is pump porosity (pump area/total area) and the error bars indicate 95% confidence intervals. The EO pumps from the SOI wafer without polysilicon were closest to the maximum theoretical flow rate prediction. The SOI design has the highest flow rate per unit area but the 375 µm thick pump design realizes the best DMFC performance. The voltage (or polarization, bottom left) and power density (bottom right) data show that activation of EO pump significantly improves DMFC performance. The maximum measured power density, 17.8 mW/cm^2, is comparable to 16 mW/cm^2 reported by Lu et al. for a conventional DMFC of similar size.