

ELECTRONIC SUPPLEMENTARY INFORMATION

Microfluidic fuel cells on paper: meeting the power needs of next generation lateral flow devices

Juan P. Esquivel,^{*ab} F. Javier Del Campo,^a José L. Gómez de la Fuente,^c Sergio Rojas,^c and Neus Sabaté^a

^aInstituto de Microelectrónica de Barcelona, IMB-CNM (CSIC), Campus UAB sn, Bellaterra, Barcelona 08193, Spain

^bDepartment of Bioengineering, University of Washington, Seattle, Washington 98195, United States. E-mail: juanpa@uw.edu

^cInstituto de Catálisis y Petroleoquímica, ICP (CSIC), Madrid 28049, Spain

Visualization of flows in Y-shape paper strip design.

The paper strip design used to build the microfluidic fuel cell is shown in the sequence of pictures in Figure S1. In this case, the device was supplied with two different color dye solutions (800 mM erioglaucine (blue dye) and 1870 mM tartrazine (yellow dye) in deionized water) to help visualizing the flows in the paper. The figure shows the advance of the two flows of solutions from the inlets to the absorbent pad. The laminar regime present in paper allows the separation of two solutions at the reaction region where the fuel cell electrodes are placed. This experiment can be viewed in Video1, also included as Electronic Supplementary Information.

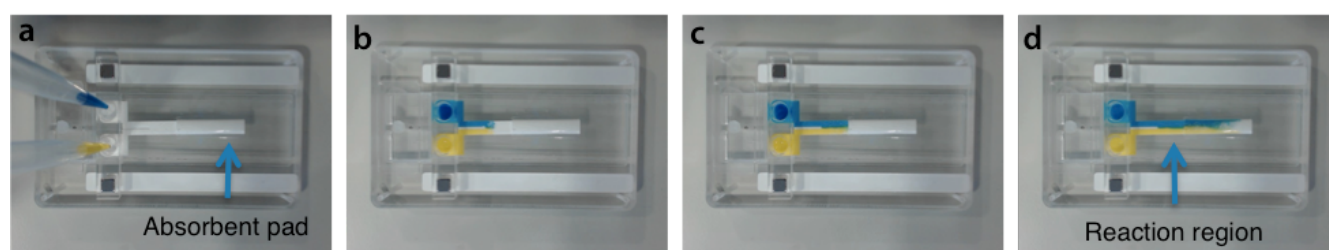


Figure S1. Laminar flow of two solutions in a paper strip.

Lateral flow test strip fuel cell design.

Exploded view of the microfluidic fuel cell shown in Figure 2b from the main manuscript, with all its components identified.

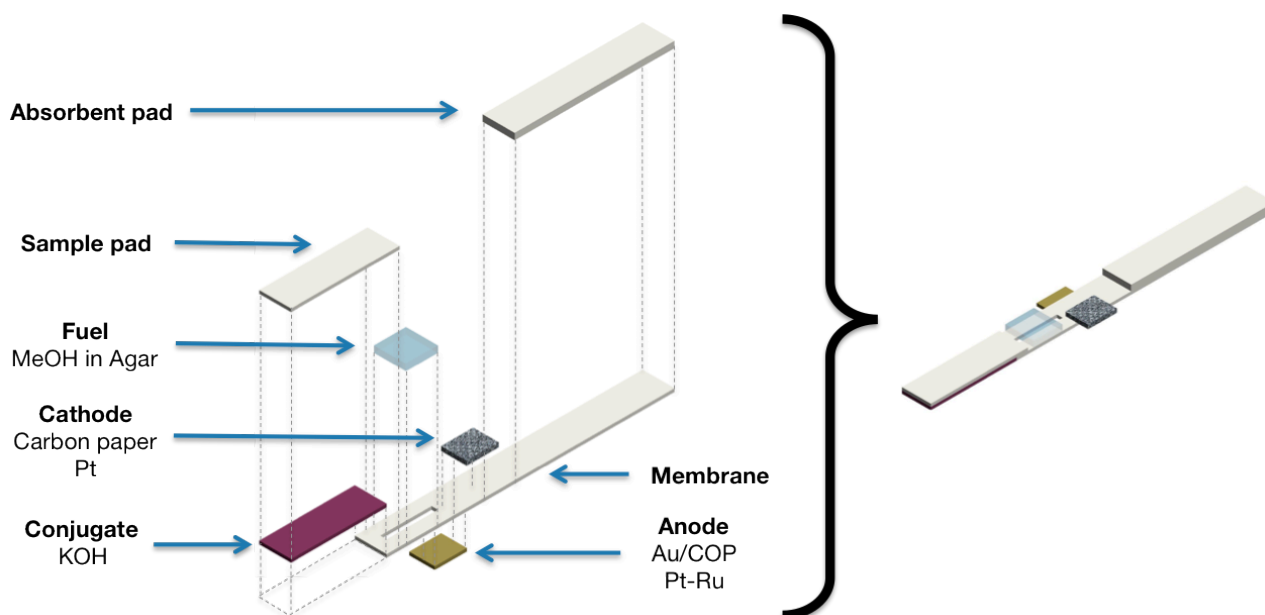


Figure S2. Exploded view of lateral flow test strip fuel cell.

Visualization of fuel release into the fuel cell stream.

The preparation of the agar gel containing methanol was similar to the procedure used for bacterial culture. In this case, 1 g of powdered agar (Sigma Aldrich) were dissolved in 50 mL of deionized water and brought to boil. A volume of 6 mL was poured on a 90mm diameter Petri dish to obtain a 1mm thick layer. After cooling down at room temperature, the gel layer was cut in 5 x 5 mm squares with a doctor blade. These gel squares were soaked in pure methanol for at least 24 h before using in the fuel cell. The gel is placed on the paper strip over the slit. In order to prevent the diffusion of methanol, the cathode side of the slit was laminated with a protective plastic layer. Figure S4 and Video2 show a representation of the release of fuel into the strip using color dyes. First, a solution of yellow dye is poured in the inlet (Fig. S4a). Then, a 5 x 5 mm piece of Fusion 5 membrane blotted with blue dye is placed on the strip (Fig. S4b). As the solution flows towards the absorbent pad, the blue dye is incorporated only in the top half of the stream, corresponding to the anode side (Fig. S4c-d).

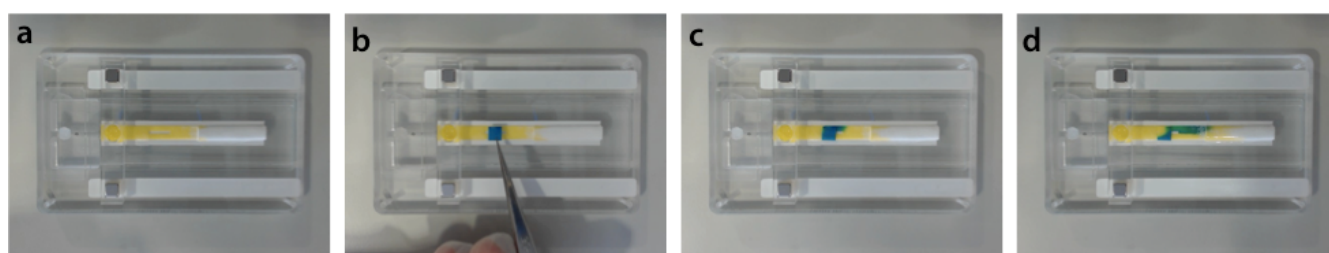


Figure S3. Visualization of the release of fuel into the water stream.

Visualization of KOH release into the fuel cell stream.

A solution of pH indicator indigo carmine (Sigma Aldrich) in water was used to evaluate the rate at which the conjugate releases KOH into the fuel cell stream. This pH indicator is dark blue at pH below 11.5 and turns yellow above pH = 14. For this experiment, a flow test strip was mounted with the KOH conjugate pad under the sample pad and an additional wicking material (Kimwipe) on top of the absorbent pad to keep a more steady flow rate. Figure S4 shows pictures of the setup at different times of the experiment that can also be viewed in Video3. A volume of 200 μL of pH indicator solution (pH: 7 – blue) was supplied on the sample pad (Fig. S4a). At the beginning, the KOH in the conjugate rapidly dissolves into the solution (Fig. S4b), which turns a strong yellow (pH > 14). As the KOH in the conjugate dissolves, the solution entering the strip turns green ($11.5 < \text{pH} < 14$) and finally stays blue (pH < 11.5), shown in Fig. S4c-f. The change in solution pH corresponds to the variations in electrolyte concentration. As it is shown in Figure 3b, the fuel cell performance is sensitive to the KOH concentration. A minimum working concentration of 1M KOH is only achieved when the pH in the solution is above 14. A lack of KOH in the solution hinders the performance of the fuel cell, as seen in the output voltage signal from Figure 3d.

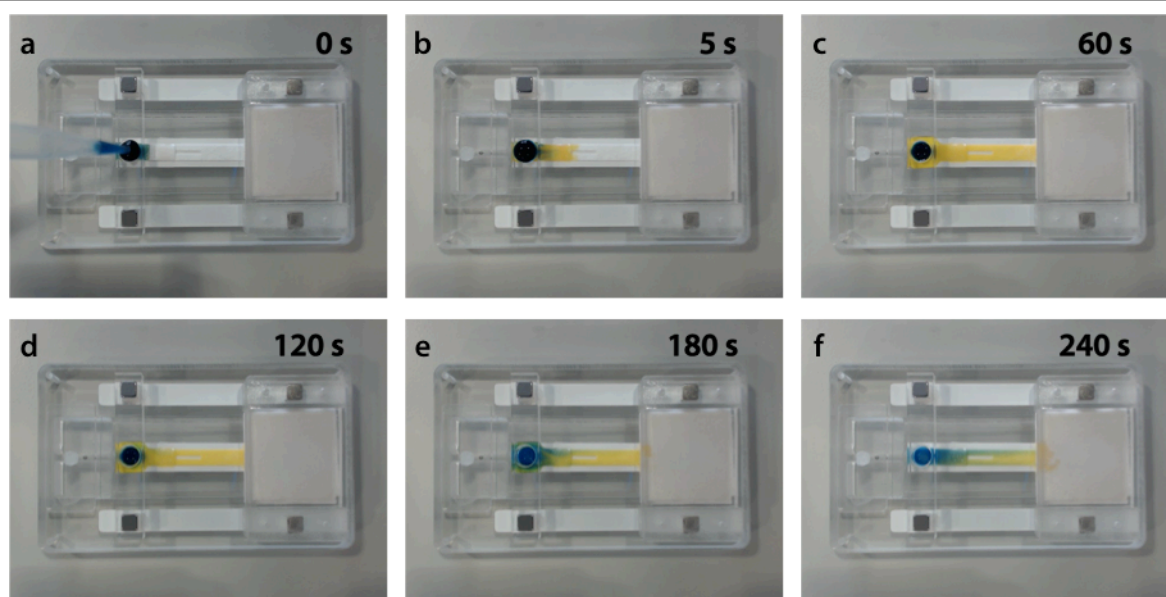


Figure S4. Visualization of the release of KOH into the water stream using pH indicator.

Electrochemical characterization of the laminar flow in a paper microfluidic channel.

It has been verified that the two streams flow independent without mixing in a single paper strip by electrochemical methods. In this measurement setup, two sets of three-band electrodes (Au-evaporated on COP) were placed under the Y-shaped paper strip (Fusion 5, Whatman). An additional absorbent (Kimwipe) was used to keep the flow rate more stable during the measurement. 250 μL solutions were supplied into each of the inlets of the paper strip, 0.5M KNO_3 (channel A) and 2mM $\text{K}_4\text{Fe}(\text{CN})_6$ in 0.5M KNO_3 (channel B), as shown in Figure S5a. As the solutions flowed parallel along the strip, the electrical response of each stream was measured by the electrodes. Figure S5b displays chronoamperometric data showing the lack of cross diffusion of reagents between the two parallel streams running along the paper strip.

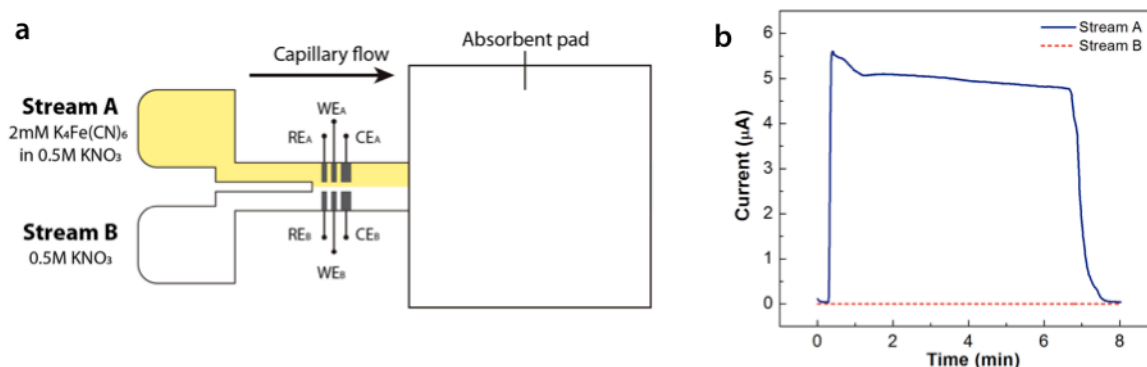


Figure S5. (a) Schematic representation of the electrochemical characterization setup with two independent flows in a single paper strip. (b) Chronoamperometry of the device using 2mM $\text{K}_4\text{Fe}(\text{CN})_6$ in 0.5M KNO_3 in one side (stream A) and 0.5M KNO_3 only in the other (stream B).

Fuel cell reproducibility

In order to assess the device performance reproducibility, multiple devices were fabricated and characterized under the same operating conditions. Fuel cell devices described in Figure 2a were tested using an anolyte solution of 2M MeOH in 1M KOH and a catholyte solution of 1M KOH. As shown in Figure S6, the variability between devices is less than 10%.

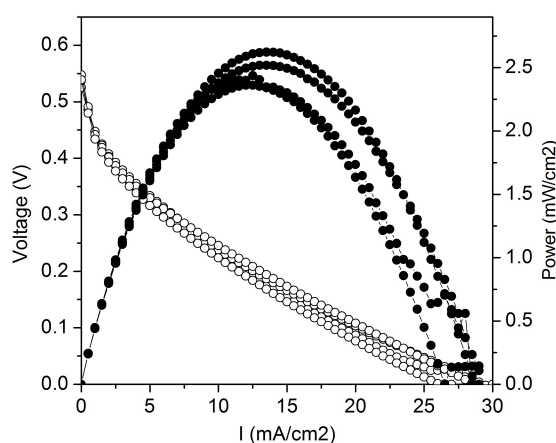


Figure S6. Polarization curves of different paper microfluidic fuel cell devices working with 2M MeOH in 1M KOH (anolyte) and 1M KOH (catholyte) at ambient conditions.

Characterization of fuel cell electrode potentials

The potentials of anode and cathode in the fuel cell were characterized using a Ag/AgCl wire as reference electrode. The potentials of each electrode were recorded during the polarization curve measurements shown in Figure 3a. Anolyte solutions were 0.5 M - 8 M MeOH in 1M KOH and catholyte solution 1M KOH.

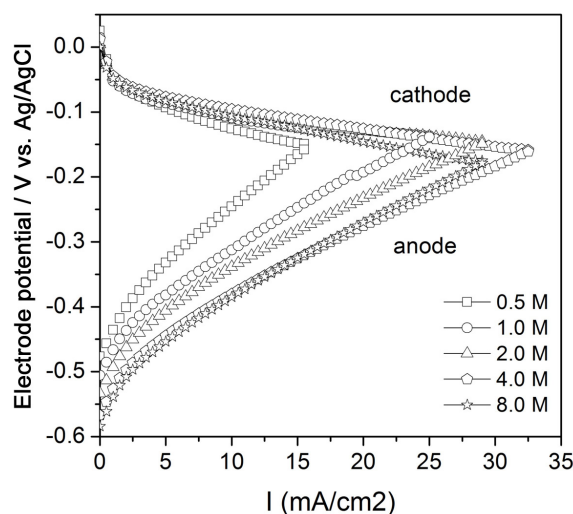


Figure S7. Current-potential characteristics of the paper microfluidic fuel cell under different methanol concentrations.

Fuel cell characterization setup

The paper microfluidic fuel cells were characterized using a custom-made acrylic setup that allowed fluidic and electrical connections using magnetic fixings. Figure S8 shows the microfluidic fuel cell described in Figure 2b prepared for characterization.

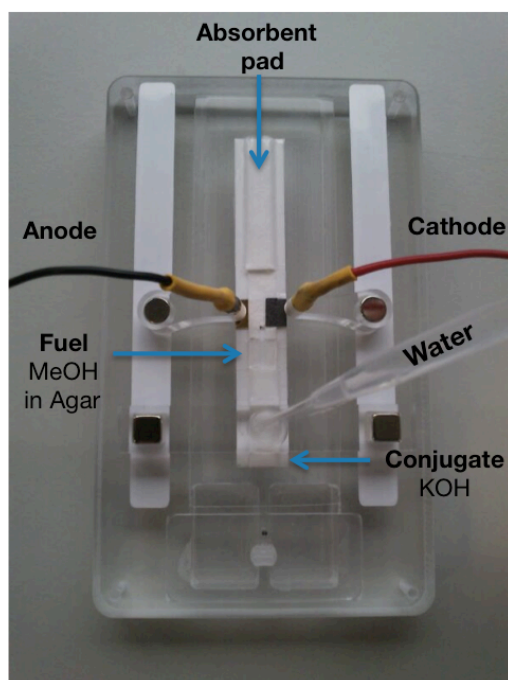


Figure S8. Picture of the paper microfluidic fuel cell under electrochemical characterization.

Table S1. Comparison of methanol microfluidic fuel cells

Anode Cathode	Fuel	Oxidant	Flow rate (mL min ⁻¹)	OCV (V)	P _{max} (mW cm ⁻²)	I@P _{max} (mA cm ⁻²)	I _{max} (mA cm ⁻²)	Features	Ref
2 mg cm ⁻² Pt/Ru 2 mg cm ⁻² Pt on graphite	1M CH ₃ OH 1N KOH	1N KOH	0.3 ^a	0.7	2.0	4	5.5	Mixed media experiments	1
2 μm Ni(OH) ₂ 2 μm AgO on gold	2M CH ₃ OH 0.2M KOH 0.05M H ₂ O ₂	2M CH ₃ OH 0.2M KOH 0.05M H ₂ O ₂	0.2 ^a	0.1	0.028	0.8		Non noble catalysts	2
10 mg cm ⁻² Pt/Ru on graphite plate 2 mg cm ⁻² Pt on carbon paper	1M CH ₃ OH 1M KOH	1M KOH	0.3 ^a	0.7	17.2	60	115	Fuel and media flexible investigation	3
2 mg cm ⁻² Pt/Ru 2 mg cm ⁻² Pt/C on Toray paper	0.75M CH ₃ OH 1M KOH	1M KOH	0.05 ^a	0.7	24.9	121	175	Electrode arrangement in air breathing fuel cell	4
6 mg cm ⁻² Pt–Ru 2 mg cm ⁻² Pt on carbon paper	5M CH ₃ OH 0.5M H ₂ SO ₄	0.5M H ₂ SO ₄	12.6 ^b (anode) 14.2 ^b (cathode)	0.92	6.5	35	62.7	Multichannel, air- breathing	5
3 mg cm ⁻² Pt/Ru/C 3 mg cm ⁻² Pt/C on carbon paper	1M CH ₃ OH 1M H ₂ SO ₄	Air	0.3 ^a	0.5	3.8	20		All polymer using Kapton films	6
1 mg cm ⁻² PtRu/C on Au/COP 1 mg cm ⁻² Pt/C on carbon paper	4M CH ₃ OH 2M KOH	2M KOH	0.080	0.55	4.4	22.5	47	Paper-based fuel cell capillary flow	This work
1 mg cm ⁻² PtRu/C on Au/COP 1 mg cm ⁻² Pt/C on carbon paper	4M CH ₃ OH 1M KOH	1M KOH	0.080	0.55	3.2	15.5	33	Paper-based fuel cell capillary flow	This work

PUMP TYPE:

^a Syringe pump (PHD2000, Harvard Apparatus, Hamden, CT)

^b Centrifugal minipump (RS 480–112)

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