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Supporting Information

A Microelectronic Sensor Device Powered by a Small Implantable Biofuel Cell

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Supporting Information

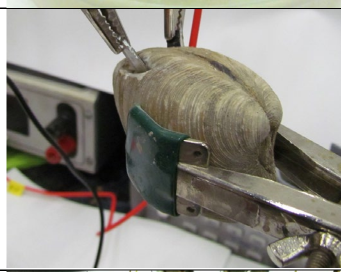
Additional explanations and calculations:

Control experiment proving the covalent immobilization of the enzymes at the polymer film. The covalent immobilization of biomolecules through carbodiimide coupling reactions is a well known and standard procedure (I. Willner, E. Katz, Integration of layered redox-proteins and conductive supports for bioelectronic applications. *Angew. Chem. Int. Ed.* **2000**, *39*, 1180-1218). In order to get experimental proof of the covalent binding of the enzymes to carboxyl-containing polymer film we performed a control experiment in the absence of EDC during the immobilization procedure. As expected, the enzymes were not immobilized and completely washed out from the electrode surface.

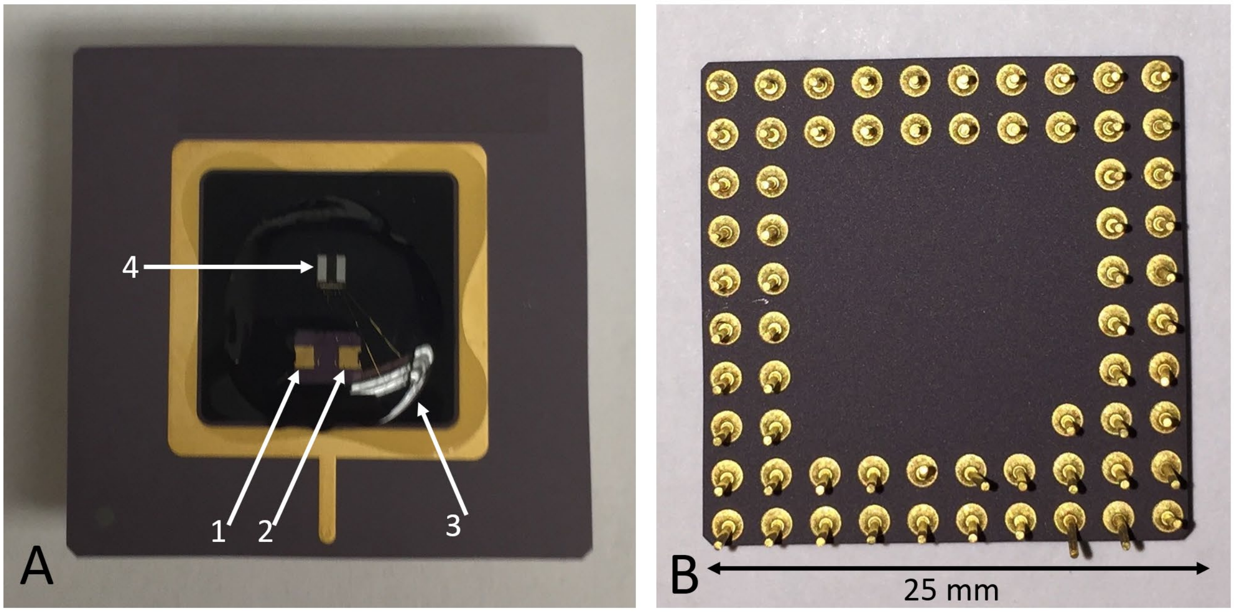
Calculation of the electronic parameters of the microelectronic device upon its operation.
The direct measurements of Vbfc, Ibfc and Icap in the microelectronic device are not possible. However, we calculated Vbfc, Ibfc and Icap using measured Vcap value as described below:
In a capacitor, voltage and current follows 'current × time = voltage × capacitance.' Thus, Icap can be calculated by (7.5 mF) × ΔVcap / Δtime. In Figure 9, from 'Beginning of measurement' to 'Activation of biofuel cell', Icap is –525 nA on average, discharging the supercapacitor. From 'Activation of biofuel cell' to 'End of measurement', Icap is +196 nA on average, charging the supercapacitor.
Before 'Activation of biofuel cell', Vbfc = OCV (0.31 V) and Ibfc = 0 since the charge pump chip does not provide current to the supercapacitor yet and does not draw any current from the biofuel cell. After 'Activation of biofuel cell', the charge pump chip outputs 721 nA in total (525 nA + 196 nA). The output power of the 'Charge Pump' chip is 1.56 μW considering the voltage of 2.16 V. Considering charge pump efficiency of 65%, the input power (Vbfc × Ibfc) is 2.4 μW. Based on Figure 8A and C, the biofuel cell operates at the maximum power point, and Vbfc = 0.21 V and Ibfc = 11.4 μA.

Wireless data transmission.
The 'Radio' chip transmits data by near-field inductive coupling. It consists of a power oscillator, a pulse generator, a current limiter, a decoupling capacitor (decap), and a controller. The power oscillator, combining the functions of frequency generation and power delivery, is implemented to replace the conventional power-hungry frequency synthesizer and power amplifier. The sensor transmitter circuit operates at 13.6 mW for the maximum output power, but the power management chip cannot support more than 1 mW. Instead, during a pulse to send a radio signal, the power oscillator draws high current from the decap, delivering strong output power to the antenna. After a pulse is transmitted, the power oscillator is shut down and the decap needs to be recharged before the next pulse is transmitted. The decap is recharged through the current limiter by less than 100 μA, which protects the operation of the power management chip. Therefore, the decap recharging time is long compared with the pulse width, and the resulting transmitted signal is a series of sparse pulses. To exploit this unique feature, the transmitter employs pulse position modulation. The controller generates a control signal to enable the power oscillator for the pulse transmission. The signal is sliced by the pulse generator to produce a tunable width pulse, which can be shorter than a controller clock period.

Table S1: Power generated by various implanted biofuel cells.

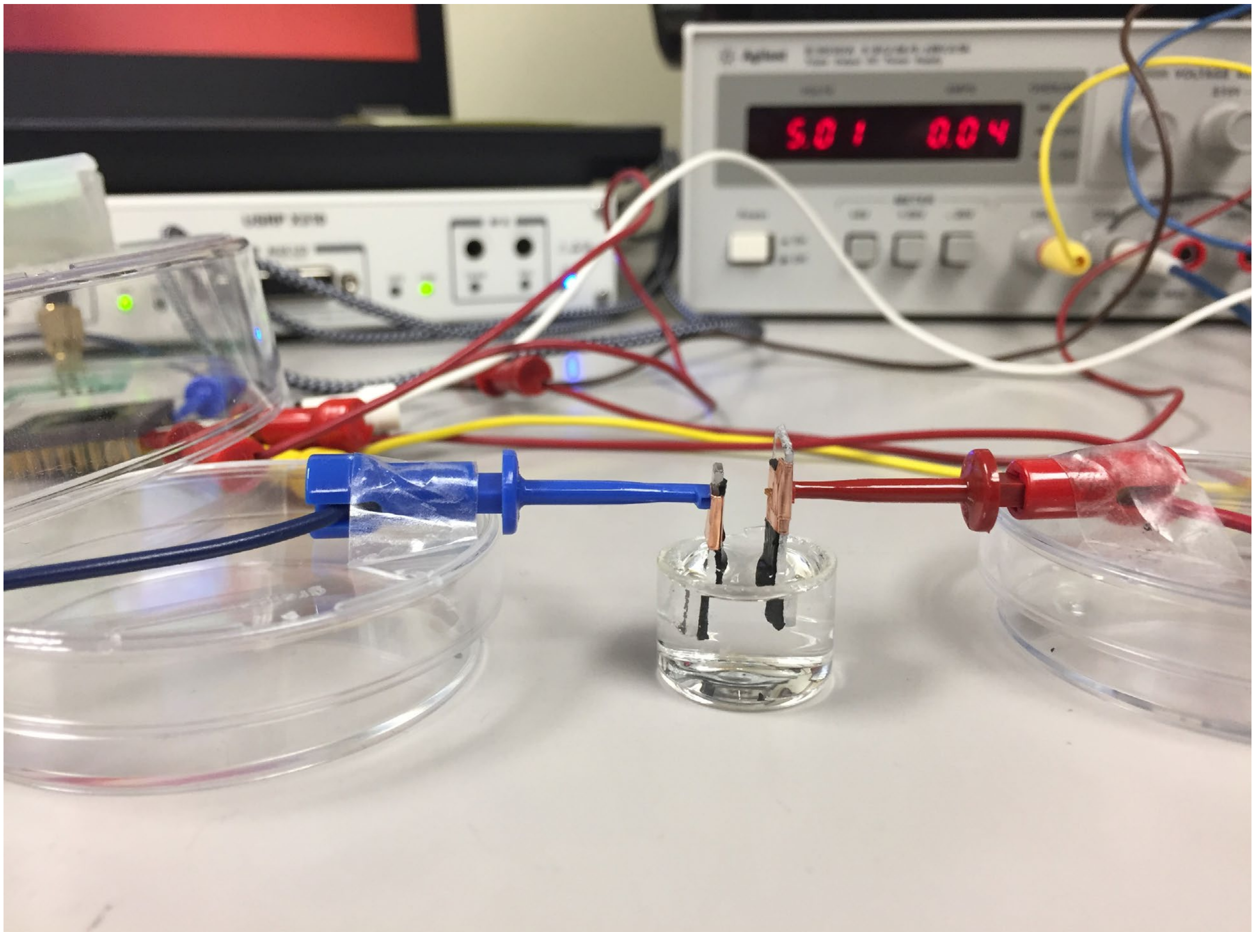
Living species	Photos	Maximum Power Production (μW)	Maximum Power Density (μW/cm²)	References
Insect		**0.11**	**15**	**24**
Clam		**5.2**	**20.8**	**26**
Snail		**7.45**	**30**	**25**
Rabbit		**0.4**	**125**	**31**
Rat		**53**	**70**	**28**
Slug		**2.4**	**40**	**Present work**

The photos in the next pages illustrate the experimental setup.

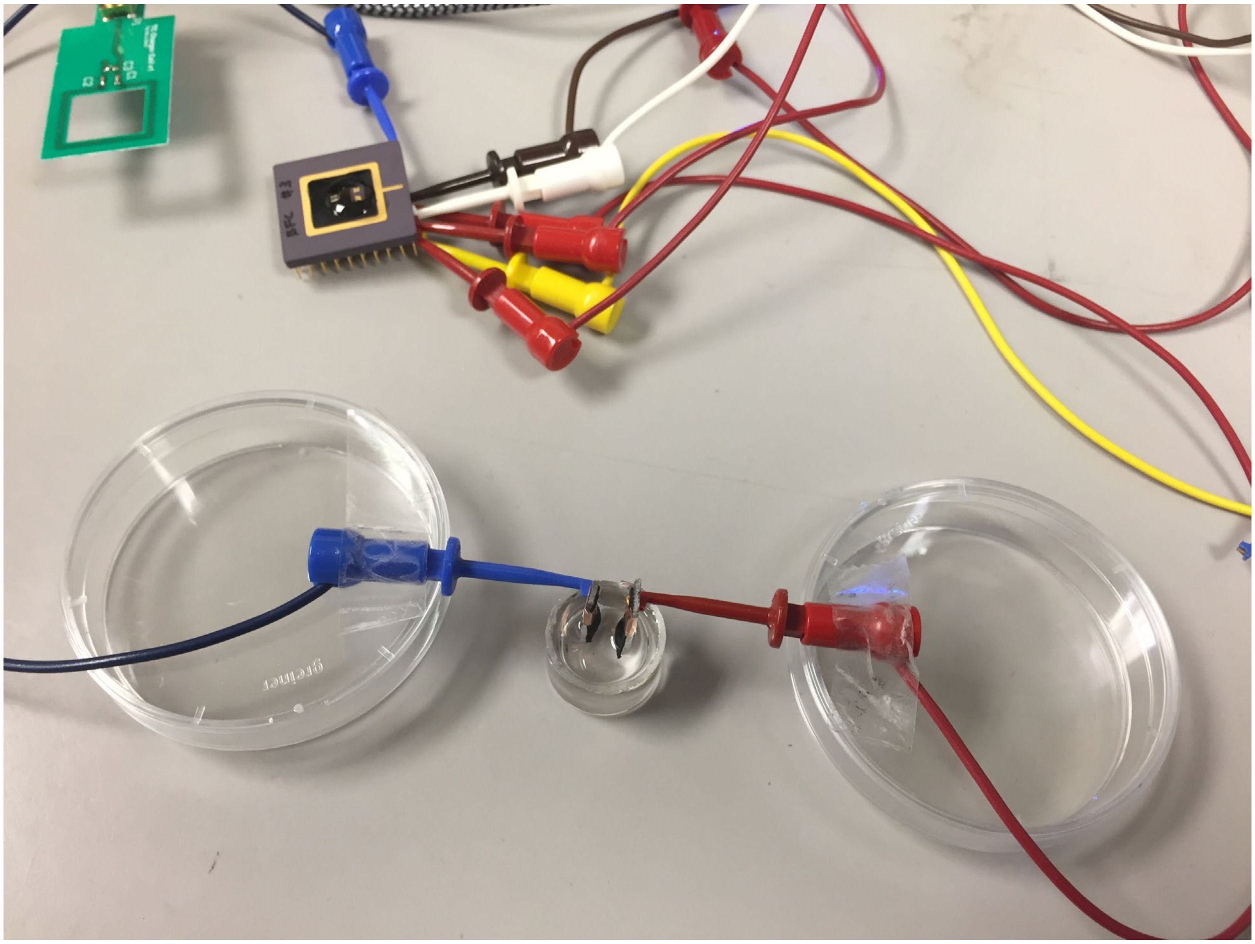


Microelectronic sensor device: (A) front view: (1) Supercapacitor (Seiko CPX3225A752D, 7.5 mF), (2) Supercapacitor (Seiko CPX3225A752D, 7.5 mF), (3) Sealant, (4) Optical receiver. (B) Backside view.

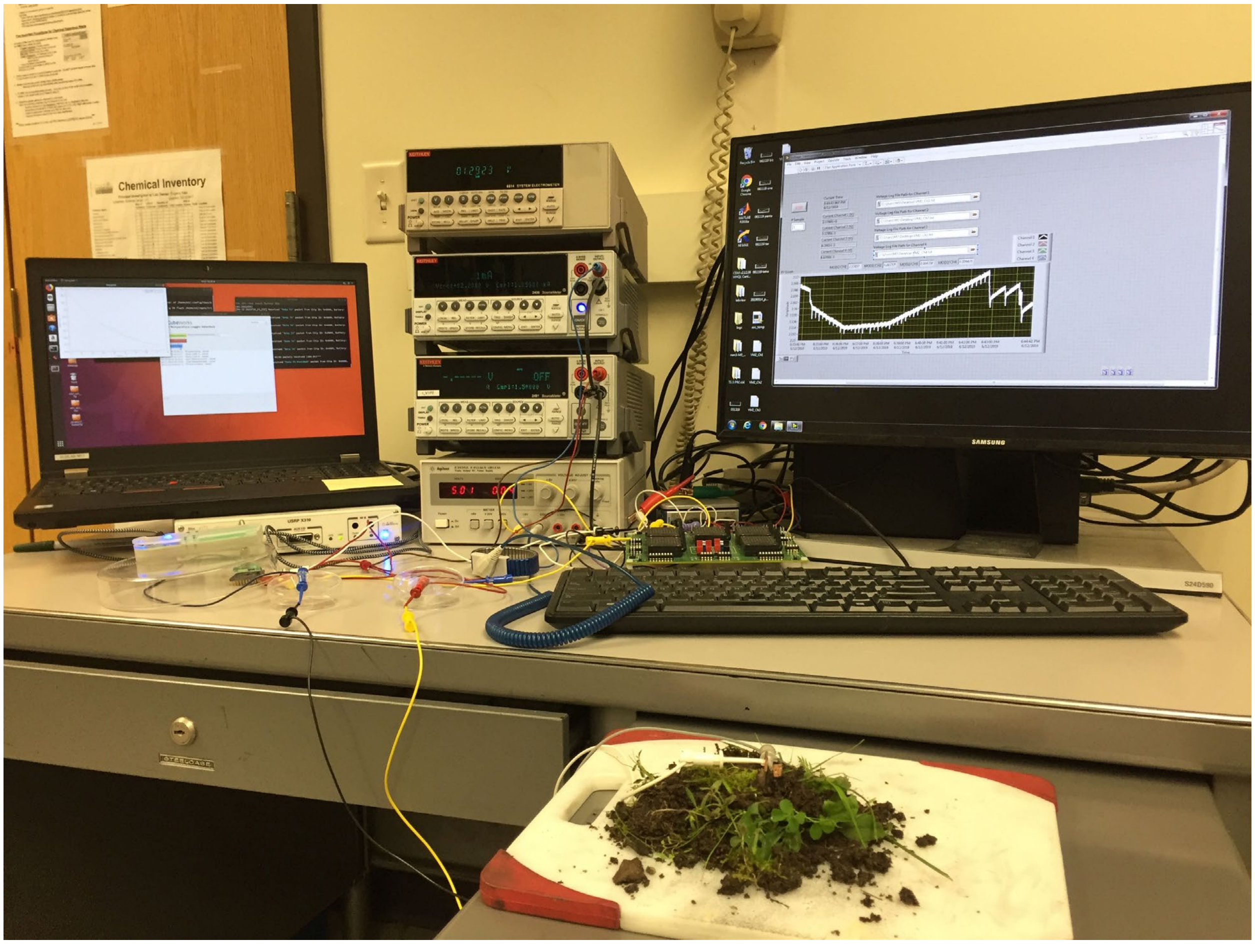
Slug with implanted biocatalytic electrodes.



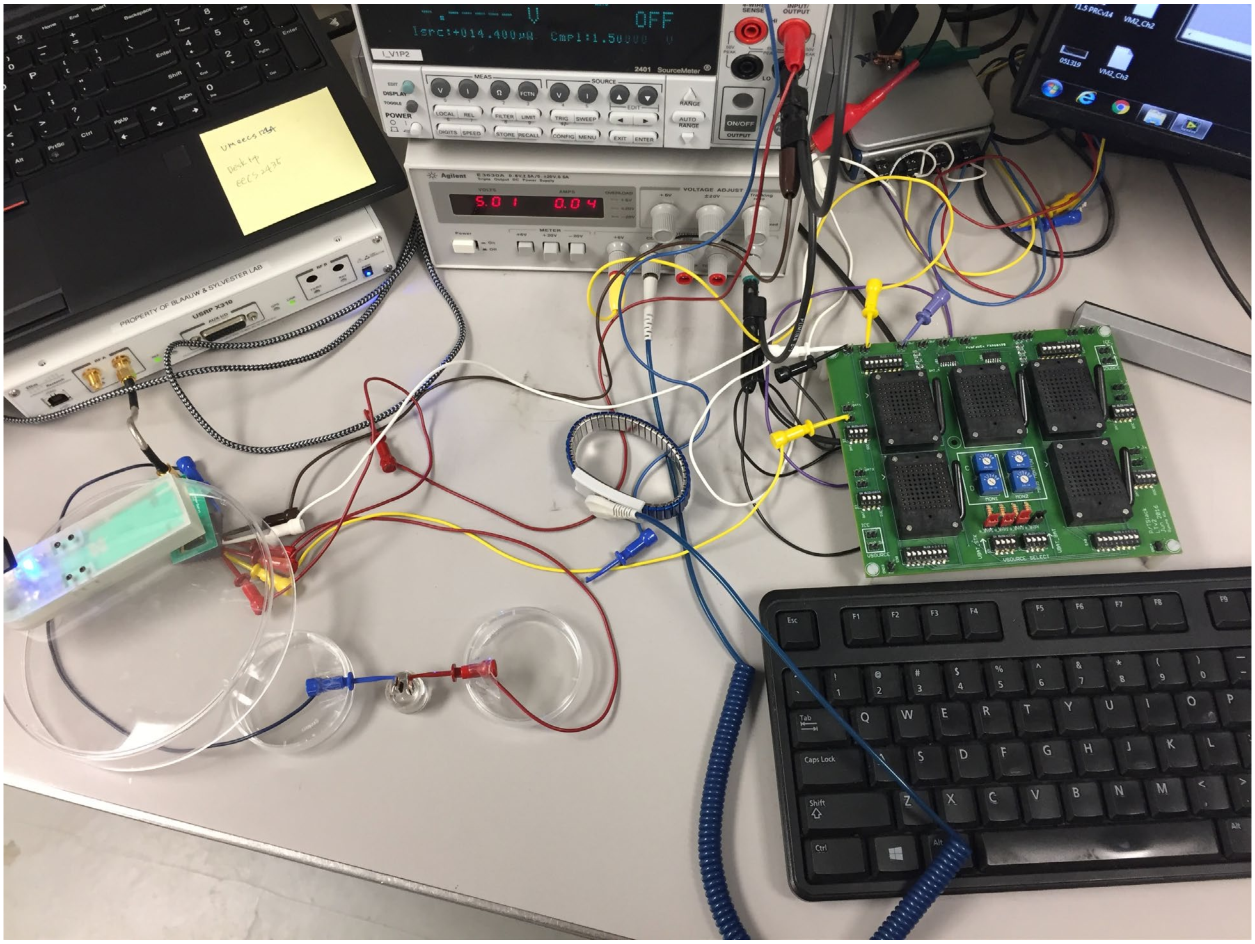
The biofuel cell operating in an aqueous model solution.



The biofuel cell operating in an aqueous model solution and the microelectronic sensor device connected to the analyzing instruments.



The biofuel cell implanted in the slug (located on ground and grass) wired to the experimental setup.



The experimental setup – top view.