A Long-Lasting Microliter-Scale Microbial Biobattery Using Solid-State Ionics

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Abstract. We report a microliter-scale bacteria-powered biobattery providing a long-term operational capability for potentially powering unattended wireless sensor networks. In a 20μL-chamber, the biobattery contained a horizontally arranged anode/salt-bridge/cathode configuration with solid-state agar electrolytes. A slow release of bacterial nutrients from a synthetic solid anolyte enabled a continuous current generation (> 6μA/cm^2) over 8 days while a liquid-based anolyte was completely depleted within 4 hours. Given that wireless sensors require an ultra-low power intermittently, our micro-biobattery can be practically used for more than a month without human intervention. Agar-based catholyte and salt bridge further enhanced the device lifespan and ensured its practical feasibility as a power source for wireless sensors. The device was sealed with a gas-permeable polydimethylsiloxane (PDMS) membrane to facilitate gas exchange to the bacteria and cathodic reactions, even ideally allowing for replenishing bacterial nutrients from environments for self-sustainable energy harvesting. Our device used *Shewanella oneidensis* MR-1 to produce a maximum power density of 4μW/cm^2 and current density 45μA/cm^2 after 96 hours (day 4), which will be enough power for small-power applications.

1. Introduction

Recent advances in wireless sensing blend various functionalities while reducing power consumption using integrated sensors on very small chips [1]. These new unprecedented sensing techniques have led to the rapid evolution of wireless sensor networks (WSNs) for the emerging Internet-of-Things (IoT) [2]. The deployment of larger-scale WSNs has reached a tipping point, even becoming ubiquitous, judging by the increasing number of studies reported in scientific publications and ideas for smart cities, smart energy, security applications, electronic healthcare and intelligent transportation [3, 4]. However, there is a significant challenge in realizing truly stand-alone and self-powered sensing networks that operate without human intervention [5]. The key challenge is the need for a micro- or nano-sized long-lasting power source for each sensing node in a more effective and efficient way. Power autonomy is critical, allowing miniaturized wireless sensors to work independently and self-sustainably in limited-resource and remote regions, in order to increase lifetimes and reduce maintenance. Micro-sized microbial fuel cells (micro-MFCs or micro-biobatteries) are the most suitable power source for underwater and floating sensors because various microorganisms can self-sustainably harvest ambient

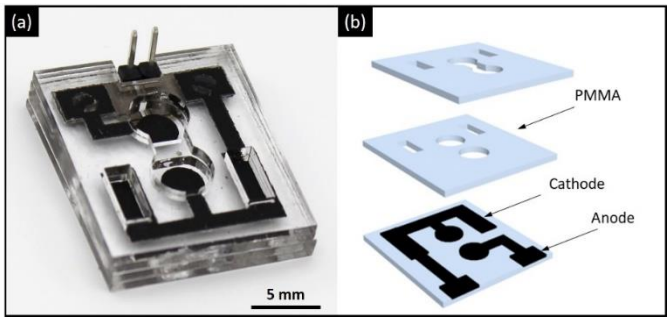

Figure 1: (a) Photo image and (b) conceptual diagram of the long-lasting biobattery.

chemical or light energy [5]. Furthermore, their power density and the output voltage are comparable to or even higher than potential energy harvesting techniques for powering WSNs. However, the promise of this technology has never been translated into practical micro-power supplies for real-world applications because of (i) the lack of a standardized micro-biobattery platform compatible with micro- and nano-fabrication, (ii) insufficient sustainable capabilities without replenishing the bacterial media, and (iii) no prior studies for showing the practical efficacy of the micro-biobatteries. In this work, a long-lasting micro-sized microbial biobattery was fabricated with a simple device design and microfabrication techniques without using a complicated fluidic pumping system by using solid-state anolyte, catholyte and salt bridge (Figure 1 & 2).

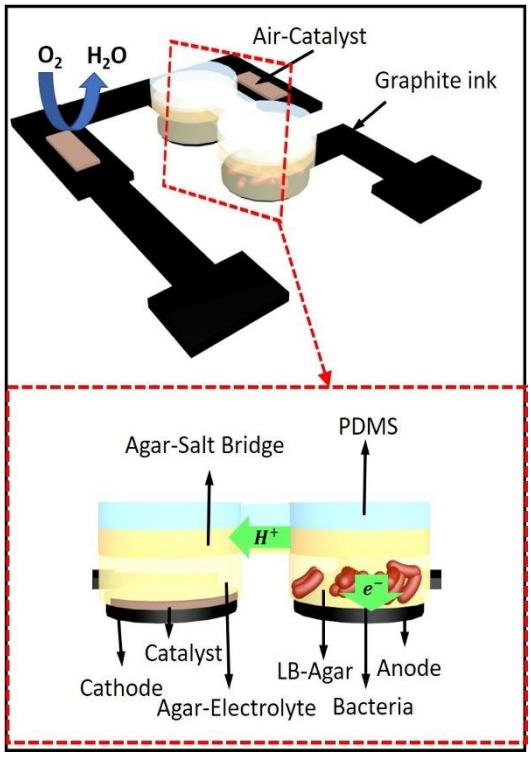

Figure 2: A working principle of the proposed biobattery. A dual-chambered biobattery consists of an anode and a cathode connected by a salt bridge. Each component is filled with a solid-state agar electrolyte. Bacteria in the anodic chamber produce electrons and protons during their respiration, which move along the external circuit and diffuse through the salt bridge, respectively, and are reduced to water at the cathode.

2. Materials and Methods

2.1. Fabrication

Figure 3 shows the fabrication steps of our solid-state microbial battery. A horizontal arrangement of the anode, the proton exchange membrane and the cathode in the micro-sized chamber was constructed to minimize the electrode distance, reduce the device internal resistance and eliminate the need for external wiring. The device consisted of three poly(methyl methacrylate) (PMMA) layers (Figure 1); (i) the screen-printed anode and cathode, (ii) the anodic and cathodic chambers and (iii) the connected reservoir for salt bridge. The cathode was prepared with the air-catalysts and was exposed to air by layer-machining windows on the PMMA. The electrolyte for the salt-bridge was injected to ionically connect the chambers. Finally, the whole chamber was sealed and covered with polydimethylsiloxane (PDMS).

2.2. Inoculum

Shewanella oneidensis were grown from -80ºC glycerol stock cultures by inoculating 20mL of L-broth

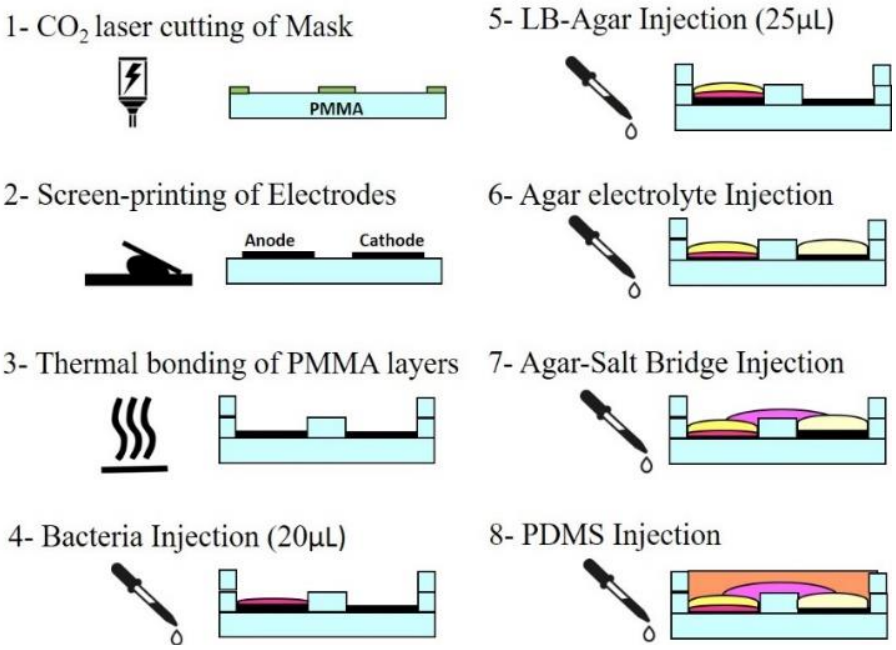

Figure 3: Fabrication steps of the proposed device

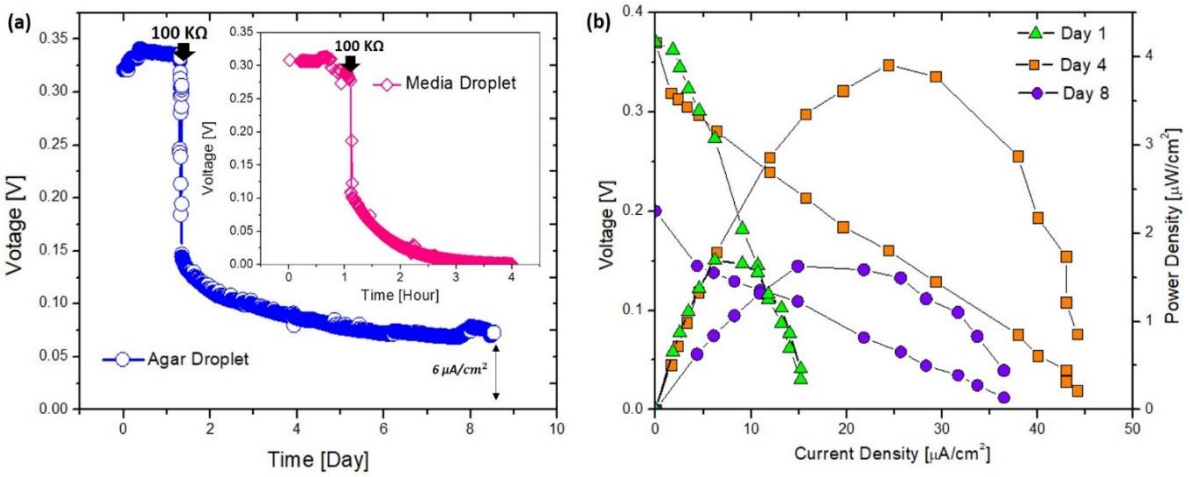

Figure 4: (a) Operational duration of the micro-biobattery with agar- and liquid-based media and (b) polarization curves and power outputs as a function of current.

medium with gentle shaking in air for 24h at 35ºC. The L-broth media consisted of 10.0g tryptone, 5.0g yeast extract and 5.0g NaCl per liter. The culture was then centrifuged at 5,000rpm for 5min to remove the supernatant. The bacterial cells were re-suspended in a new agar-based medium and used as a solid-state anolyte for the device. The agar-based medium contained L-broth media with 1.5% (w/v) bacterial grade agar. The salt-bridge was also based on the solid-state agar containing 5% (w/v) NaCl.

2.3. Measurement setup

The potentials between the anodes and the cathodes were measured with a data acquisition system (National Instrument, USB-6212), and recorded the readings every 1 min via a customized LabView

interface. An external resistor connected between the anode and the cathode closed the circuit. The current through this resistor was calculated using Ohm's law.

3. Results and Discussion

After preparing the microliter-solid state chamber, the open circuit voltage (OCV) was monitored and recorded for one day to allow for performance stabilization (Figure 4a). The instant OCV of ~0.3V was rapidly achieved and stabilized in a few hours of operation. After reaching the stable OCV, we connected a 100kΩ resistor between the anode and cathode to allow the current flow. The longevity of our solid-state agar-based device was compared to the conventional liquid-based device. Our agar-based biobattery in the microliter-scale chamber demonstrated an 8-day lifetime without fluidic pumping systems and human maintenance, while the liquid-based device had the life-time of less than 4 days. Figure 4b shows polarization curve and power output of the battery, which was derived and calculated based on the maximum current value at a given external resistance. The maximum recorded power density was obtained after 4 days of operation (4μW/cm^2).

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