

Power-on-paper: Origami-inspired fabrication of 3-D microbial fuel cells

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ABSTRACT

We demonstrate that fabricating low-cost microbial fuel cells (MFCs) can be done efficiently by using a paper substrate and origami techniques. A 3-D MFC was developed from a 2-D sheet of paper by integrating the anode, reservoir, cation exchange membrane (CEM) and air-cathode. The cell was easily formed by folding the paper along pre-defined creases. The entirely paper-based all-printed MFC developed in this work rapidly generated power with a small amount of bacteria-containing liquid through rapid adsorption and instant attachment of the bacteria cells to the anode. A graphite-polymer composite and graphite ink with activated carbon were readily applicable as novel anodic materials on paper and enhanced performance better than a conventional graphite ink or gold anode. The hydrophobic wax-based CEM was readily built with a commercially available wax printer and using heat to control how deep the wax penetrated the paper. This work will create a novel platform for paper-based power source, stepping toward batch-fabricable flexible papertronics.

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1. Introduction

Microbial fuel cells (MFCs) are rapidly gaining acceptance as an alternative green energy technology, as they generate electric power from a broad range of organic waste materials under natural conditions [1,2]. MFCs employ live microorganisms to efficiently catalyze the degradation of the organic compounds, offering clean and sustainable energy independent of fossil fuels or solar illumination. The organic fuel for microorganisms can be any type of biodegradable substrate including wastewater, urine, or soiled water from a puddle. In addition, river, ocean or pond water generally hosts various microorganisms that can transfer electrons via metabolism to an external electrode. For this reason, MFCs are regarded as a promising energy source in resource-limited environments [1]. There is a growing interest in miniaturizing MFCs to take advantage of microfluidics and microfabrication techniques [3–5]. Their low-cost, environmentally friendly features and easy power accessibility in those challenging field conditions make the small-scale MFCs suitable for powering portable devices or on-chip

microfluidic systems. Furthermore, they inherently produce favorable conditions for high power generation; a large surface-to-volume ratio, high reproducibility, efficient mass transport, and low internal resistance [6]. A miniaturized MFC will provide power – without an external service – for truly stand-alone, self-sustaining, portable and small electronic systems even in the most resource-constrained settings.

Despite their vast potential, miniaturized MFCs have not been integrated with practical power applications because of several key issues. First, their configuration is complicated by the necessary multifunctional parts (anode, cathode, gaskets, and ion exchange membrane) and the microfluidic tubing for liquid inlets and outlets. Furthermore, miniaturizing the MFC has many challenges, including microfabricating ion exchange membranes and gaskets, which demand manual assembly of MFCs and hamper batch fabrication [7]. Also, bonding or clamping each functional component remains challenging. All these fabrication issues increase design complexity which makes them high-cost devices. Second, MFC operation requires additional power and equipment to continuously transport and control organic fuels. Fluidic manipulation can be controlled efficiently by micropumps or other components. However, these active components require significant

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external energy at the tens of mW to several Ws level, which is much higher than the power generated from the MFC itself [8]. Third, even small-scale MFCs require several hours to days to accumulate and acclimate microorganisms on the anodic surface [9]. Although miniaturized MFCs integrated in a microfluidic device dramatically decrease the start-up time from their macroscopic counterparts (a few weeks), even that is not enough for on-site practical applications. If one of the biggest arguments for the miniaturized MFCs is the potential for practicability as a portable power supply, then there is a clear and pressing need to discover powerful yet simple methods for on-demand bacterial power generation.

This paper demonstrates a technique that overcomes all three of these limitations by preparing all MFC components on a single sheet of paper and folding the 2-D sheet for a 3-D MFC (Fig. 1). An entirely paper-based, all-printed MFC platform was developed, simplifying fabrication and operation, decreasing production cost, and revolutionizing MFC applications for portable on-demand power generation. Furthermore, the device uses the capillary force to flow liquid without external pump, power and tubes. In addition, the device rapidly generated power with a small amount of bacteria-containing liquid through rapid adsorption by the paper and the instant attachment of the bacterial cells to the anode. The 2-D sheet paper included four functional foldable tabs; ① anode, ② reservoir, ③ cation exchange membrane (CEM), and ④ air-cathode (Fig. 1). The 3-D MFC was directly created from the 2-D sheet of paper by folding along pre-defined creases. Anodic materials were simply screen-printed while the reservoir and the CEM were easily patterned with hydrophobic wax on the paper. An activated carbon based air-cathode was constructed at the top of the sheet. Our novel origami technique for fabricating 3-D structured MFCs resolved challenges identified in the miniaturized MFCs and our first generation paper-based MFC platforms [10–13]. Our previous paper-based biobatteries were made by manual stacking of multi-layer papers, generating many potential issues such as misalignments of paper layers and incompatibility of batch fabrication. Even a single sheet of paper battery was suffered from extremely low power generation (nW level) [14]. The innovation foreseen by this current work is outside the scope of our previous projects, which proposed to use paper as a new material substrate for the biofuel cells. This work represents the fusion of the art of origami and paper-based MFC technology, which could provide a paradigm shift in the architecture, material, and design of integrable and stackable paper-based batteries. Furthermore, the proposed battery will enable the development of new types of powered, paper-based biosensing assays in convenient, easy-to-use packages. In this work, we also conducted electrical and morphological investigations of five anodic material candidates to determine which made the MFC perform best. Furthermore, the ion transfer resistance and the electrical performance of the wax-based CEM in the

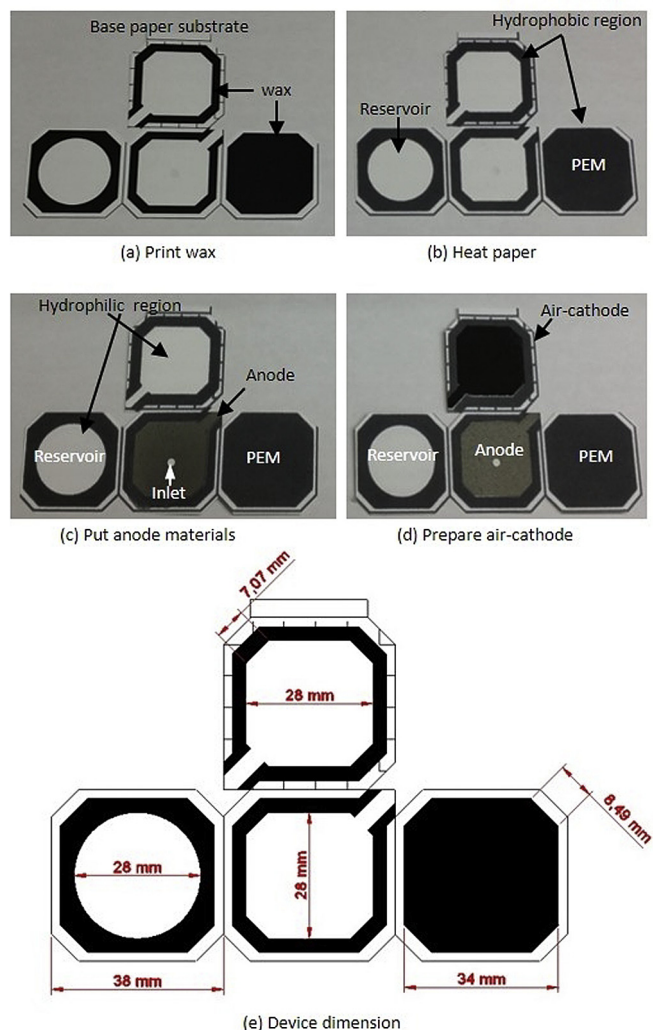


Figure 2. (a) – (d) Fabrication processes of the paper-based MFC and (e) the device size.

device was thoroughly examined and compared to that of the commercial Nafion 117 membrane.

2. Experimental procedure

2.1. Device fabrication and operation

First, the 2-D sheet of paper (Whatman #1 filter paper) was

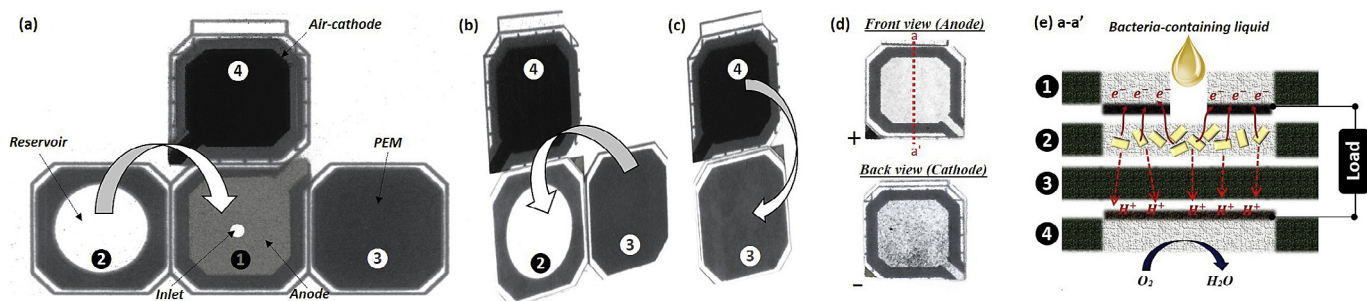


Figure 1. (a) – (d) Origami fabrication of the paper-based MFC and (e) schematic diagram of a cross section of the assembled device and its test setup.

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