A 1-D Yarn-Based Biobattery for Scalable Power Generation in 2-D and 3-D Structured Textiles

Jihyun Ryu, Yang Gao, Jong Hyun Cho, and Seokheun Choi, *Senior Member, IEEE*

***Abstract*— The next generation of textile-based wearable batteries will be built on 1-D fiber/yarn through a bottom-up approach. Functional yarn fibers will be weaved or knitted into 2-D or 3-D batteries of a large textile, but the bottom-up strategy from 1-D yarn fibers is at a very early stage and requires a long-term focus. Here, we demonstrate an innovative 1-D yarn biobattery, a step toward a potential solution for scaling-up production of the wearable batteries. Our 1-D biobattery used microorganisms as a biocatalyst to harvest electrons from microbial metabolism. This yarn biobattery can be easily scaled up by weaving functional yarns into 2-D or 3-D batteries, connecting multiple batteries in series and parallel. [2020-0084]**

***Index Terms*— Biobattery, bacteria-powered, yarn-based, textile, microbial fuel cell.**

I. Introduction

OVER the last decades, there has been a wealth of development breakthroughs in the field of smart textiles [1]–[4]. A wide range of promising applications have been demonstrated in healthcare, consumer electronics, internet of things (IoTs) and soft robotics [5]. A key enabling factor for these developments is the seamless integration of the microelectronics into fabrics. Contrary to the conventional attachment methods, functional fibers capable of sensing, actuating, communicating and computing components will ultimately be assembled onto the smart textiles [6]. Thus, an equal counterpart providing continuous and sustainable power is indispensable for the truly self-reliant and stand-alone smart textiles [7], [8]. Intended for the seamless integration into smart textiles, many fiber- and yarn-based energy harvesting techniques based on photovoltaic [9], thermoelectric [10], piezoelectric [11], triboelectric [12], [13], and biocatalytic effects have been reported. Among them, there are microbial fuel cells (MFCs) and biobatteries that generate electricity from the biodegradation of organic matters [14], [15]. Despite their distinguishing advantages including self-regenerating biocatalyst, versatile choice of organic matter as the fuel sources, and the continuous electricity-generating capability independent from light, mechanical motions, or temperature differences, the MFCs and biobatteries suffer from a large

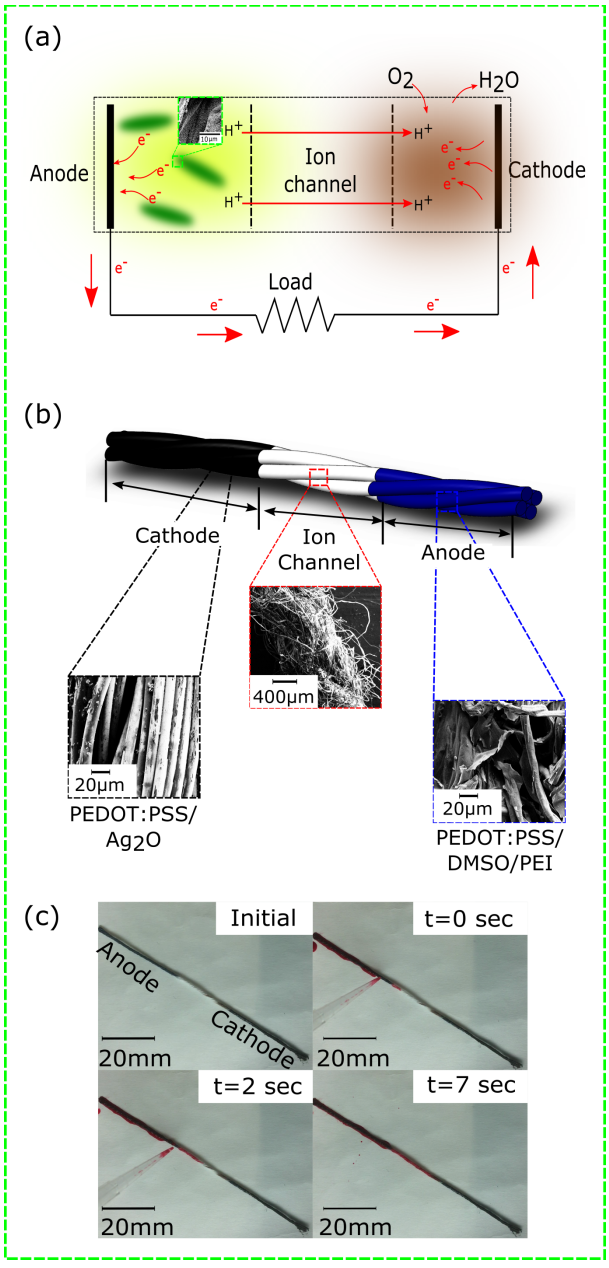

Fig. 1. (a) Working principle of the 1-D yarn-based biobattery. (b) Schematic diagram and corresponding SEM images of the yarn-based biobattery. (c) Wicking property of the 1-D biobattery.

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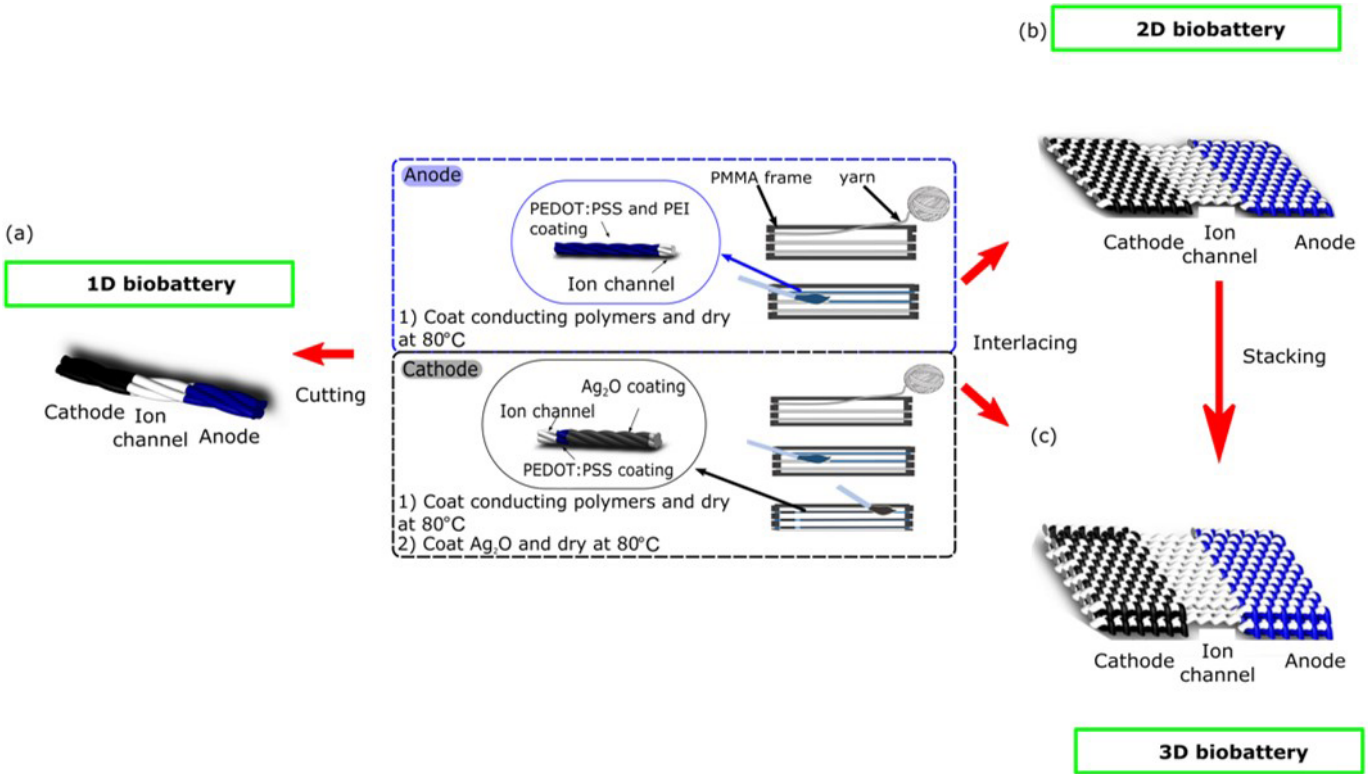

Fig. 2. Schematic illustrations of the fabrication process for scalable yarn-based biobatteries. (a) a 1-D device (b) a 2-D device, and (c) a 3-D device.

device footprint due to their multiple-yarn designs and low output power densities which incur further difficulties for integration and hamper the mass production of large-scale textile applications [7].

In this work, we report a scalable 1-D yarn-based biobattery which produces electricity from the biocatalytic metabolisms of *Shewanella oneidensis* MR-1. The single-yarn 1-D biobatteries were woven together forming higher-dimensional 2-D and 3-D biobattery stacks with the augmented power and current outputs, offering a versatile new avenue for energizing the future smart textiles.

II. Materials and Experimental Set-Up

A. Working Principle of Yarn-Based MFCs

Resembling the configurations of the traditional MFC [16], [17], the yarn-based 1-D biobattery consists of three different sections: (i) anode, (ii) cathode, and (iii) ion exchange microfluidic channel (Fig. 1a). When the bacterial inoculum was introduced onto the anode, living bacterial cells reduced the organic matters and produced protons and electrons which diffused and transferred to cathode, completing the close circuit for the bioelectricity generation.

B. Preparation of Anodic and Cathodic Inks for Device Fabrication

To define the electrodes on the insulating 1-D yarns (Fig. 1b), we deposited each end of the yarn with conducting polymers. The conductive ink was prepared by mixing 1 wt % PEDOT:PSS (Clevios PH1000, Heraeus) with 5 wt% dimethyl sulfoxide (DMSO, Sigma-Aldrich), followed by ultrasonication to achieve a highly conductive homogeneous mixture [18], [19]. For a cathodic compartment, an electron acceptor ink was prepared by mixing silver (I) oxide powder (Sigma-Aldrich) in 1 wt% PEDOT:PSS sonicating them for 60 minutes [20]. The silver-based conductive paste ink was further treated with heating and stirring (60 °C, 110 rpm) to increase the weight percentage of PEDOT:PSS from 1 wt% to 2 wt%.

C. Wicking Property of Cotton Yarn

Owning to the tightly braided fiber strands, the intrinsic liquid wicking capability of the 1-D yarn device allowed an ion exchange without any external driving force. When the anolyte was introduced into the anode, the bacterial cells were accumulated and acclimated on the conductive and hydrophilic fibers. The wicking property was characterized by using a red food dye (Fig. 1c). Within 7 seconds, the dye was flowed to the cathode. Without additional surface treatment, the average wicking rate of the yarn-based device was 0.43 mm/s when 80 μL of aqueous solution was applied, which almost doubled the rate of as-received cotton yarn.

D. Device Fabrication

Commercial cotton yarns were immersed in 70 v/v% ethanol and sonicated for 30 minutes, followed by drying in a ventilated oven at 80°C to remove a water-repellent grease and to obtain a sterile device for the microfluidic flow transportation. To functionalize many 1-D yarns with an identical dimension

(Fig. 2a), we wrapped the cleaned yarns around the grooves patterned on polymethyl methacrylate (PMMA) frame to hold them firmly in tension on. To obtain electrical conductivity and hydrophilicity for the even and rapid distribution of the bacterial sample throughout the anodic region of the yarn, we used a mixture of PEDOT:PSS and DMSO. When the mixture ink was fully dried, we added diluted polyethyleneimine (PEI, Sigma-Aldrich) to the anodic component. The PEI enabled the reduction of conductive ink, resulting in the consistent output performance by shortening the time of bacterial reduction. The Ag_2O-PEDOT:PSS electron acceptor ink was additionally brushed onto the other part of the yarn to form a cathodic part, leaving a pristine region between the anode and the cathode as the ion channel.

We used traditional weaving techniques to scale up the 1-D device into a 2-D platform (Fig. 2b). The woven structure was the simplest and easiest format for a large-scale smart textile by readily interlacing functional yarns. Similar to the fabrication of the 1-D biobattery, we wrapped a cleaned yarn around the PMMA frame and then the functional anodic and cathodic yarns were weaved through the cleaned yarns. A 3-D device was also realized by stacking the 2-D structured devices in a vertical direction that eventually formed a parallel connection (Fig. 2c).

E. Bacterial Inoculum

S. oneidensis MR-1 stored at -80°C glycerol stock was inoculated in 20 mL of Luria broth (LB) medium consisting of 10 g of tryptone, 5.0 g of yeast extract, and 5.0 g of NaCl per liter. The bacteria were cultured in 30°C for 24 h and diluted with fresh media until the OD_{600} reached 2.8.

F. Data Acquisition and Measurement Setup

The potential difference between the anode and cathode was measured by a data acquisition system (DI4108U, DATAQ Instruments). To determine the current generated by the device, external resistors were used to connect the anode and cathode, and a current flow through the resistor was calculated by Ohm's law.

III. Results and Discussion

The 1-D biobattery was readily connected in series and parallel, improving its performance (Fig. 3). To build a series connection (Fig. 3a, & 3b), two or three individual devices were formed in a single yarn and conductively linked by brushing the graphite ink between the anode of one device to the cathode of another device. The dried graphite ink prevented the exchange of ions at the junctions of series-connected batteries. For the parallel configuration (Fig. 3c), individual devices were placed in the same direction where all anode and cathode terminals were clipped for the connection.

When *S. oneidensis* MR-1 inoculum was introduced to the anode, the capillary action rapidly transported the liquid throughout the anodic region. Electrons were harvested from the bacterial metabolism in the conductive anodic region, which flowed to the cathode via the external circuit. The

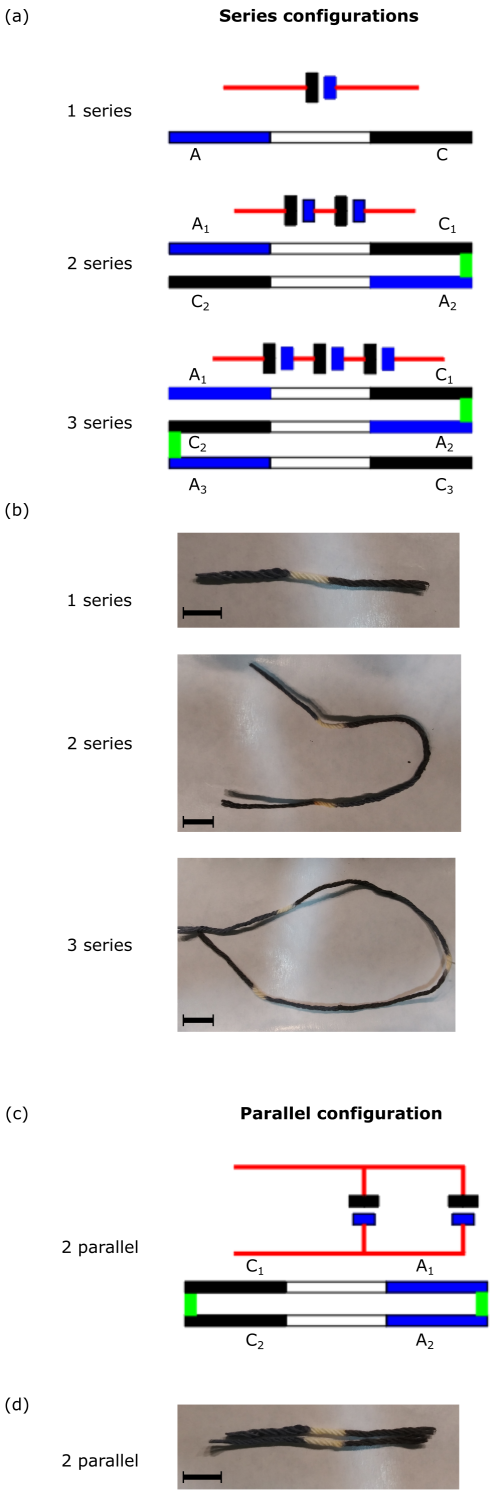

Fig. 3. Schematic illustrations and photo-images of (a & b) series and (c & d) parallel configurations.

other microbial byproducts, protons, generated in the anode internally flowed to the cathode through the microfluidic ion channel, reducing Ag_2O to Ag [20].

We confirmed the bioelectricity generation from *S. oneidensis* MR-1 respiration by testing a control without bacterial cells. Each experiment was repeated three times

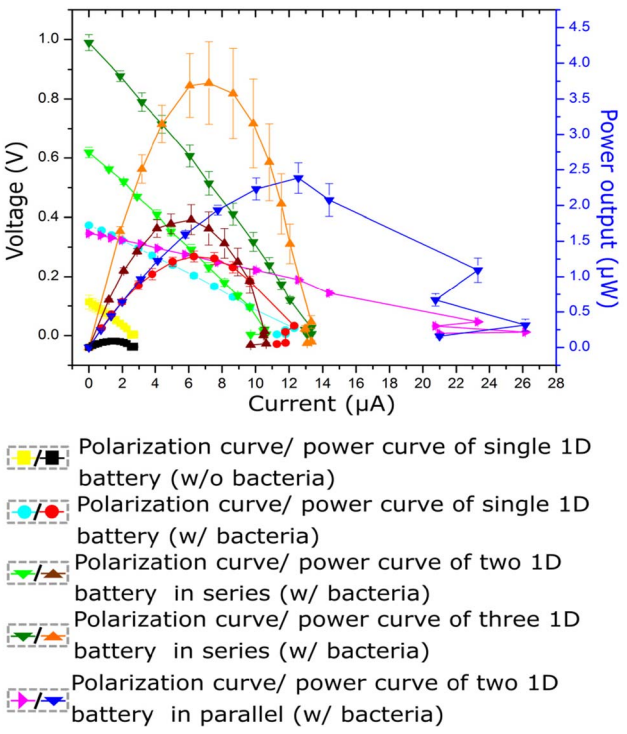

Fig. 4. Performances of the 1-D yarn-based biobatteries. Polarization and power curves of the biobatteries connected in series and parallel.

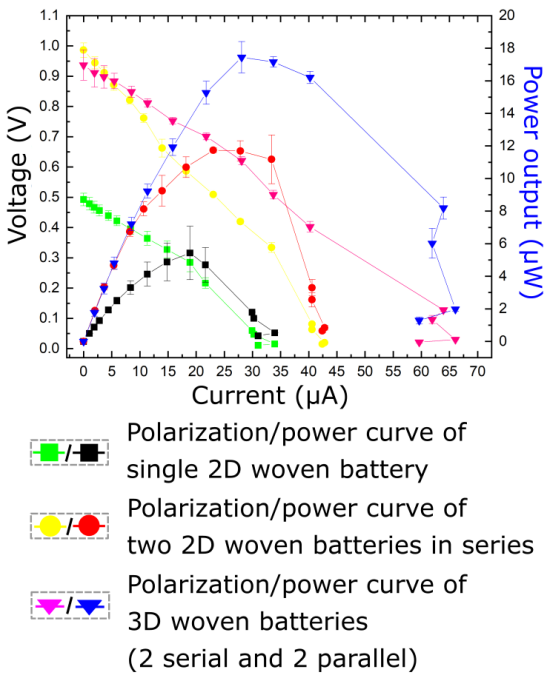

Fig. 5. Polarization curves and power outputs of 2D/3D biobatteries.

to verify the consistency of the results. The open circuit voltages (OCVs) of the single biobatteries with and without *S. oneidensis* MR-1 were 113 mV and 374 mV, respectively (Fig. 4). The corresponding power outputs were 0.1 μW and 1.2 μW, respectively (Fig. 4).

When two and three 1-D biobatteries were connected in series (Fig. 4), the OCV, maximum current and power outputs were measured at 618 mV, 10.5 μA, 1.80 μW and 989 mV, 13.3 μA, 3.72 μW, respectively. For the parallel connection of two and three biobatteries, the corresponding OCV, max current and power outputs were 346 mV, 23.3 μA, 2.38 μW and 355 mV, 32.5 μA, 3.13 μW. The voltage measurements and power outputs resulted from the series connection were proportionally increased with the number of devices while the current outputs were relatively stable. In contrast, for the parallel configuration, the current and power outputs were increased with the number of devices while the voltage was unchanged.

Similarly, the series/parallel connections of the 2-D woven structural devices were performed (Fig. 5). From the polarization test of the single 2-D woven structure, we confirmed that *S. oneidensis* MR-1 generated 503 mV for OCV and 34 μA, 5.5 μW for max. current and power, respectively. The serially connected 2-D devices produced a higher output performance with 1 V for the OCV, and 45.5 μA and 11. 8 μW for the maximum current and power respectively. Additionally, a 3-D battery could be easily scaled up by stacking two serially connected 2-D batteries, significantly increasing the power performance with the maximum current and power of 67.9 μA and 17.4 μW, respectively.

IV. Conclusion

In this work, we demonstrated 1-D yarn-based biobatteries, which could be readily connected in series and parallel and be weaved into 2-D and 3-D fabric-based biobatteries. Bacteria inoculated in the anode harvested electrons from their metabolism while the electrons were transferred to the cathode through the external circuit. Although flexibility and stretchability of the devices need to be further characterized, this new biobattery represents a viable bioenergy source that could significantly improve the performance and the practicability of smart textiles.

Acknowledgment

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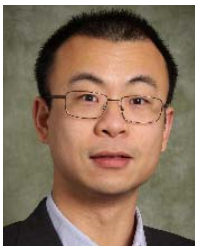

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