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A liquid-activated textile battery for wearable biosensors

X Liu¹ and P B Lillehoj¹

Department of Mechanical Engineering, Michigan State University, East Lansing, MI, USA

E-mail: lillehoj@egr.msu.edu

Abstract. Wearable biosensors is an emerging field which offers great potential for many applications including human health monitoring, environmental sensing and bioagent detection. An important requirement for these systems is the need for robust, lightweight batteries which can be easily integrated with wearable materials (i.e. textiles). In this paper, we demonstrate a new textile Ag-Al battery which is activated by liquids. Experiments were performed to optimize the battery performance by altering the device parameters, such as the electrode/electrolyte area and electrolyte concentration. Based on these results, we developed a single-cell battery that can produce a voltage of 1.3 V. By connecting two cells in series, we could power a 1.6 V LED for up to 30 minutes.

1. Introduction

In the past decade, the field of wearable sensors has made substantial progress [1]. Much of the work in this area is focused on human health applications, mainly, monitoring physiological parameters such as heart rate [2], respiratory rate [3] skin temperature [4], and blood pressure [5]. Recently, the concept of ‘wear and forget’ [6] was introduced which aims to design wearable sensors that don’t compromise user comfort or distract them from routine activities. Toward this end, researchers have been developing sensors fabricated directly onto flexible substrates including plastic films [7], wearable textiles [8] and even temporary tattoos [9]. While these devices demonstrate the feasibility of creating flexible sensors, a major challenge that remains is powering these systems, which is currently achieved using batteries.

Conventional portable batteries (NiCd, NiMH, Li-ion) typically consist of metallic electrodes, separators and electrolytes housed within a metal or aluminium casing, and these rigid components hinder their integration with flexible materials. Hence, new materials, such as carbon nanotube/polyaniline composites [10] and carbon nanotube films [11], have been explored for the development of flexible energy storage devices. Flexible batteries based on textiles have also been demonstrated which utilize solid polymer electrolytic layers [12, 13]. While promising, these batteries still pose limitations for wearable biosensor systems since they require additional circuitry for start/stop operation and are not suitable for aqueous conditions.

Alternatively, liquid-activated paper batteries have been demonstrated [14, 15] where the application of an aqueous solution causes the device to turn ‘on’. This approach enables on-demand power generation and can simplify overall device design. These batteries could provide voltages of 1.21 V with a 1 k Ω load and 1.3 V with an open circuit, respectively. To improve the durability and integration with wearable materials, we demonstrate a new liquid-activated textile Ag-Al battery. Our textile battery can be fabricated using inexpensive materials and methods, which can significantly lower overall device costs. Additionally, this battery can be activated using different types of liquids, broadening its versatility for various biosensing applications.



2. Materials and Methods

2.1. Designing the battery

The electrochemical cell consists of three layers of cotton/polyester textile sandwiched between two metal foil electrodes (Ag and Al), which serve as the anode and cathode (Figure 1). Two layers of textile are impregnated with silver nitrate (AgNO_3) and aluminum chloride (AlCl_3) respectively, to serve as dry electrolytes, and one layer is impregnated with sodium nitrate (NaNO_3) to serve as a salt bridge. The cell is sheathed between two additional layers of fabric, which are held together using double-sided tape. When liquid is applied to the cell, the dry electrolytes become hydrated and an electrochemical reaction is generated. The chemical reaction for the battery at the anode (oxidation) and cathode (reduction) are represented by equations (1) and (2), respectively:

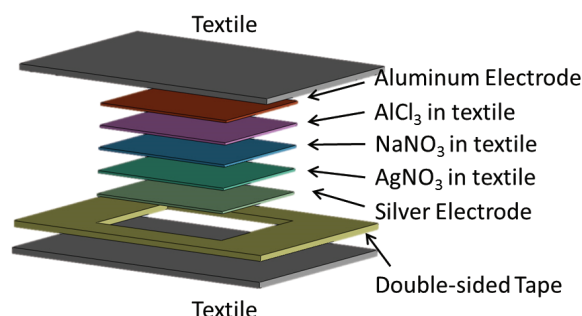
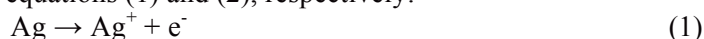


Figure 1. Schematic illustration of the textile battery.

2.2. Materials

Al foil, Ag foil, AlCl_3 , NaNO_3 and AgNO_3 were purchased from Sigma-Aldrich (St. Louis, MO). Cotton/polyester fabric was purchased from Jo-Ann Fabrics (Hudson, OH) and double-sided tape was obtained from Intertape Polymer Group (Marysville, MI). Deionized (DI) water was generated using a Barnstead Smart2Pure water purification system and phosphate buffered saline (PBS) was purchased from Thermo Scientific.

2.3. Fabricating the battery

Ag and Al electrodes, cotton/polyester fabric and double-sided tape were cut into $6 \text{ mm} \times 6 \text{ mm}$ pieces. A square hole was cut in the double-sided tape to provide access for the activation liquid. The fabric pieces were soaked in separate solutions of AlCl_3 , NaNO_3 and AgNO_3 for 1 minute and air dried overnight at room temperature. The fabric and electrodes were stacked together, as shown in Figure 1, and sheathed between two $18 \text{ mm} \times 12 \text{ mm}$ pieces of fabric. Prior to assembly, the metal electrodes were sanded to remove any surface oxidation.

2.4. Experimental procedures

For electrical measurements, wires were soldered onto the anode and cathode of the electrochemical cell and connected to a Fluke 87-V digital multimeter using alligator clips. To activate the cell, $20 \mu\text{L}$ of liquid was applied to the middle of the cell using a pipette. Measurements were performed after ~ 30 seconds, which was sufficient time for the liquid to fully hydrate the dry electrodes and activate the battery. The data was averaged over 3 individual measurements and plotted as the mean \pm standard deviation (SD).

3. Results and Discussions

Experiments were carried out to optimize the performance of the battery by studying the influence of various battery parameters on the maximum output current. For all of these studies, the electrode area was fixed at 36 mm^2 and the salt bridge was fabricated from fully saturated NaNO_3 solutions.

3.1. Influence of electrode/electrolyte area on battery performance

As shown in Figure 2, we observed a linear correlation between the electrolyte area and the short circuit current for electrolyte areas from 18 mm² to 209 mm². For electrolyte areas larger than 36 mm², there was no significance increase in the current. These results suggest that the electroactivity of the cell is affected by the ratio of the electrode/electrolyte surface area where a ratio of ≤ 1 is needed to maximize the electrochemical reactions occurring between electrodes and the electrolytes. For these studies, the concentration of AgNO₃ was 3 M.

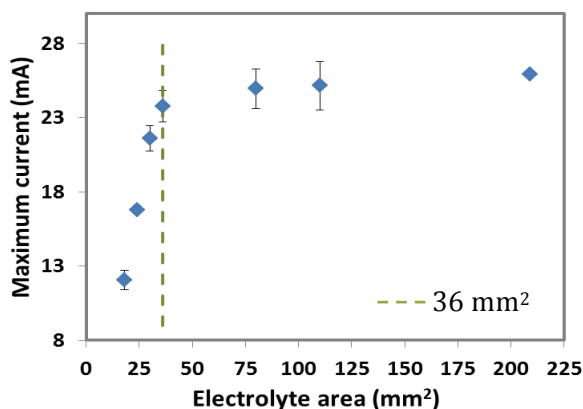


Figure 2. Maximum electrical current as a function of electrolyte area for a single cell battery activated using DI water. The electrode area is 36 mm² and the AlCl₃ electrolyte concentration is 1M. Each data point represents the mean \pm SD of three measurements.

3.2. Influence of electrolyte concentration on battery performance

Experiments were also carried out to investigate the effect of the electrolyte concentration on the short circuit current of the electrochemical cell. For these studies, the concentrations of AgNO₃ and AlCl₃ were fixed at a 3:1 ratio to balance the reaction rate (during the reaction, Ag loses one electron while Al gains three electrons) and maximize the efficiency of the half-reaction. As shown in Figure 3, our results show a linear correlation between the electrical current and the concentration of AlCl₃ from 0.5 M to 1.5 M. For AlCl₃ concentrations above 1.5 M, the output current levels off, which could be due to the saturation of the electrolyte species. This could also be attributed to issues we encountered when fabricating the AgNO₃ dry electrolyte where AgNO₃ solutions at concentrations > 4.5 M became very viscous, limiting its ability to be absorbed into the textile.

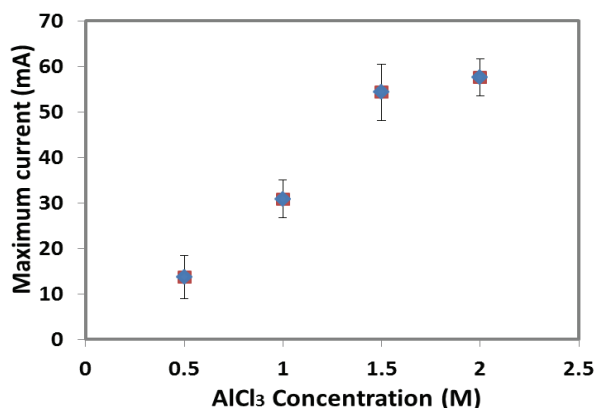


Figure 3. Maximum electrical current as a function of AlCl₃ concentration for a single cell battery activated using DI water. The electrode and electrolyte areas are 36 mm². Each data point represents the mean \pm SD of three measurements.

3.3. Influence of liquid conductivity on battery performance

The impact of liquid conductivity on the battery performance was briefly studied by activating the battery using three different types of liquids: DI water (0.0055 mS/m), tap water (5-50 mS/m), and PBS (~1,600 mS/m). As shown in Figure 4, no noticeable difference in the output current was observed for these three types of liquids. These results indicate that the liquid conductivity has a minimal effect on the performance of the battery, suggesting that this platform could be useful for various biosensing applications which utilize different types of aqueous samples.

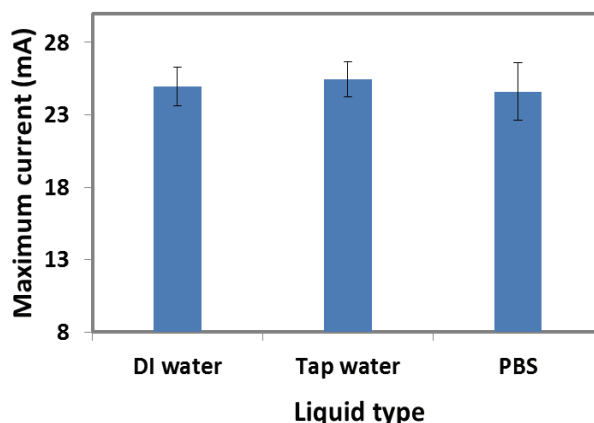


Figure 4. Maximum current from a single cell battery activated using different types of liquids. The electrode and electrolyte areas are 36 mm². Each bar represents the mean \pm SD of three measurements.

Based on the optimized parameters obtained from the studies above, our single cell battery can produce a maximum open circuit voltage of 1.3 V. A unique feature of our liquid-activated battery is that it enables on-demand power generation where current is generated only when the electrolyte is hydrated. When the liquid has fully evaporated, the chemical reactions within the cell cease and the battery shuts 'off'. The battery can simply be reactivated (at 1.3 V), by applying more liquid to the cell. This process can be repeated several times which demonstrates the multiuse capability of this platform. To demonstrate the functionality of this technology, we connected two cells in series and used it to power a 1.6 V LED, which could remain lit for up to 30 minutes (Figure 5). Typically, biosensing measurements last tens of seconds to a couple of minutes [16], therefore, our textile battery can provide enough power for multiple bioassay measurements or continuous temporal sampling over long durations.

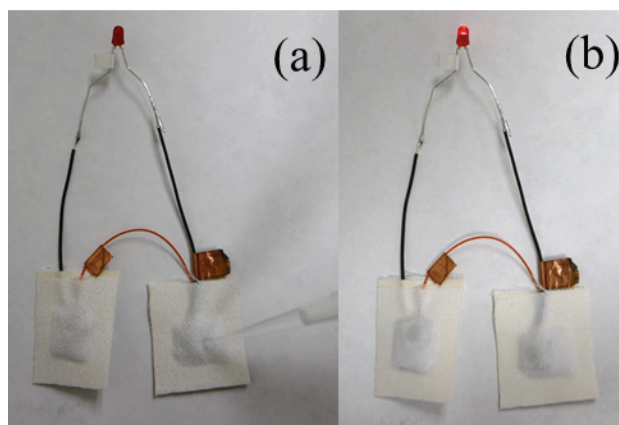


Figure 5. A two-cell textile battery connected to a LED before (a) and after (b) activation using 20 μ L of DI water.

4. Conclusions

In this paper, we introduce a new liquid-activated Ag-Al textile battery which can produce a maximum open circuit voltage of 1.3 V. By connecting two cells in series, this battery could power a 1.6 V LED for up to 30 minutes. Studies to optimize the battery revealed that its performance is influenced by the electrode/electrolyte area and the electrolyte concentration, but not by the conductivity of the activation liquid. One of the unique features of this textile battery is its mode of activation, which is initiated by simply applying a liquid sample to the cell. This approach enables on-demand power supply where the battery turns 'on' only when a liquid sample is applied, and turns 'off' when the liquid has fully evaporated. This capability makes our textile battery suitable for various biosensing applications requiring multiple measurements or continuous temporal sampling over long periods of time. Furthermore, this battery can be easily integrated with sensors fabricated on textiles and fabrics, thereby minimizing the overall size, weight and complexity of wearable sensor systems.

Acknowledgments

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