IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

Received April 4, 2018, accepted May 15, 2018, date of publication May 21, 2018, date of current version June 19, 2018.

Digital Object Identifier 10.1109/ACCESS.2018.2839078

Power Generation for Wearable Electronics: Designing Electrochemical Storage on Fabrics

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The work of C. K. Sen was supported by NIH Awards under Grants NR015676 and NR013898.

ABSTRACT We report a new class of textiles with electrochemical functions which, when moistened by a conductive liquid (saline solution, sweat, and wound fluid), generate dc voltage and current levels capable of powering wearable electronics on the go. Contrary to previously reported power generation techniques, the proposed fabrics are fully flexible, feel and behave like regular clothing, do not include any rigid components, and provide dc power via moistening by readily available liquids. Our approach entails printed battery cells that are composed of silver and zinc electrodes deposited onto a polyester fabric to generate power in the microwatt range. Electrochemical characterization of the discharge of a single printed battery cell in a 10 M sodium hydroxide (NaOH) electrolyte shows reproducible results with a sustained power level of $\sim$80 μW for over 3 h. Scalable dc power may also be achieved by connecting multiple battery cells in series via flexible and conductive E-threads. Indeed, a series connection of two battery cells is demonstrated to boost the generated voltage from 1.4 to 2.5 V. Notably, this in-series printed battery arrangement is shown to successfully power a digital thermometer under 10 M NaOH, a 0.5 M sodium chloride solution (mimicking human sweat), and Dulbecco's phosphate-buffered saline solution (mimicking bodily fluid electrolytes). Overall, the proposed technology is expected to be of utmost significance for healthcare, sports, military, and consumer applications, among others.

INDEX TERMS Conductive threads, electrochemical devices, energy storage, flexible electronics, power generation, wearable sensors.

I. INTRODUCTION

Wearable electronics are becoming increasingly popular for consumer, sports, and healthcare applications [1]–[3]. In fact, the International Data Corporation (IDC) predicts shipment of over 240 million wearable devices (smart watches, bracelets, socks, shirts, etc.) by 2021 [4]. As is well known, one of the biggest challenges associated with these wearable devices relates to the way of powering them [5], [6]. Conventional batteries are typically employed, but they are bulky and rigid, and, thus, obtrusive for wearable applications.

Alternate power-generating technologies are recently being explored, but they exhibit several drawbacks. For example, solar energy harvesters occupy large surfaces, require bulky/rigid energy-collecting panels, and only collect energy at certain times of the day [7]. Another popular method, namely Radio-Frequency (RF) power harvesting, requires an RF source within close proximity of the wearer, exhibits low efficiency, and requires bulky/rigid circuitry to perform the AC-to-DC conversion [8]. Wearable biomechanical energy harvesting technologies have also been reported [9], [10]. These harvesters capture energy from human motion (foot strike, limb motion, or joint motion) and typically rely on nano-triboelectric [11] or piezoelectric [12] actuation, converting naturally available mechanical energy to electrical energy directly. Nevertheless, these solutions still require bulky components that inhibit the flexibility of the wearable's they power.

In this work, we introduce a new path to unobtrusively powering wearable electronics by integrating electrochemical functions onto textiles [13]. The proposed method involves printing silver- and zinc-based electrodes (cathodes and anodes) on fabrics to generate DC power when moistened by a conductive liquid (saline solution, sweat, wound fluid, etc.) [14]–[16]. The conductive liquid serves as an electrolyte,

enabling ion flow between the anode and cathode. Flexible inter-connections between several of the printed battery cells allow one to connect them in series or parallel to achieve desired voltages and current, per the application requirements. Such inter-connections may be ubiquitously realized on the fabric via conductive E-threads [17], [18]. To our knowledge, this is the first time that fully-flexible batteries are implemented directly on fabric and activated via readily available bodily fluids (saline solution, sweat, wound fluid, etc.). Example applications include T-shirts and leggings that power up sensors while the wearer is exercising and sweating (accelerometers, gyroscopes, heart rate sensors, etc.) [19], epidermal pads that trigger an alarm when the underlying wound opens up [20], [21], or smart diapers that assist in toilet training for kids with autism [22], [23].

The rest of the paper is organized as follows. Section II describes the operating principle of the proposed electrochemical fabrics. Section III discusses fabrication of these electrochemical-storage-integrated fabrics. Section IV provides measurement results, including discharge experiments, feasibility of DC power scalability, and a proof-of-concept demonstration of powering a digital thermometer. The paper concludes in Section V.

II. OPERATION PRINCIPLE

The operation principle of the proposed fabric with integrated electrochemical functions is summarized in Fig. 1. The main element of this approach is a printed battery cell (see Fig. 1(a)) that is composed of two electrodes deposited onto a fabric. Inspired by our previous work [14]–[16], the electrode materials used to realize the anode and cathode are selected as zinc (Zn) and silver oxide (Ag_2O), respectively. When the electrochemical fabric comes into contact with an ionic conducting liquid, the latter acts as an electrolyte. This means that the Ag_2O cathode will undergo a reduction process, while the Zn anode will be oxidized. In turn, ionic current will flow through the electrolyte to balance the charges at the anode and cathode. The circuit will close when flexible conductive E-threads [17], [18] (marked as ''electrical connections'' in Fig. 1) are used to connect a sensor or other device to the battery's electrodes. In this particular case, electrons will flow through the E-threads, serving as current collectors for the DC power to be utilized. The aforementioned oxidation-reduction process is outlined in (1) and (2) for an example case where NaOH is used as the electrolyte. That is, DC voltage and current can be generated just by getting the electrochemical fabric moistened via an ionically conducting liquid (saline solution, sweat, wound fluid, etc.).

$$Ag_2O + H_2O + 2e^- \rightarrow 2Ag + 2OH^- \quad (1)$$

$$Zn + 2OH^- \rightarrow ZnO + H_2O + 2e^- \quad (2)$$

Incorporating engineering concepts into the design of the printed battery cells can boost/scale the generated DC power levels depending on the application. For example, a voltage boost can be achieved by connecting two or more of the printed battery cells in series. An illustration of this principle is shown in Fig. 1(b). Such connections among different battery cells may be implemented via flexible and conductive inter-connects, such as conductive E-threads [17], [18] and/or inks [24].

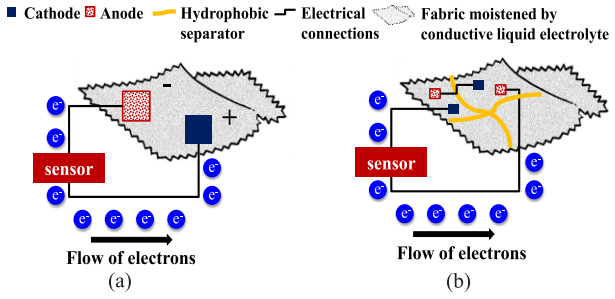

FIGURE 1. Operation principle of the proposed electrochemical fabrics with power generation capabilities: (a) Realization of a single printed battery cell. (b) Example series connection of two printed battery cells aiming to boost the generated voltage.

III. ELECTROCHEMICAL FABRIC FABRICATION

A. FABRICATION OF A SINGLE CELL

In order to create a conductive paste that can adhere onto a polyester fabric, a standardized method for making battery electrode slurry is employed [25]. First, the solid form of the electrode (Zn or Ag_2O) is crushed to fine powders using a mortar and pestle. Then, a binder such as polyvinylidene fluoride (PVDF) in an n-methyl-2-pyrrolidone (NMP) solvent is added to the powder to form an ink that can be screen-printed, hand-printed or printed using an inkjet printer. In this work, a typical ratio of 90 wt.% active materials and 10 wt.% PVDF is experimentally determined to provide maximum conductivity while still allowing the electrodes to adhere to the fabric. The desired ink viscosity is tuned by adding and removing the NMP solvent. For screen- or hand-printed electrodes, the ideal ink attains a paste-like viscosity.

The Zn and Ag_2O inks are deposited onto a medical-grade polyester fabric via hand-printing or screen-printing. Medical-grade polyester fabrics are used in order to provide maximum bio-absorbability (absorb on-body sweat), however most conventional clothing fabrics (cotton, silk, and linen) can be potentially used instead. Once the electrode inks are deposited, the cloth is dried at 100 °C for one hour. The dry weight of the Zn electrode was standardized to 30 mg (90 wt%) and up to 300 mg for Ag_2O (90 wt%). The standardized dry mass of the metal slurries was chosen to provide sufficient battery capacity to power a sensor for several hours using Zn as the limiting reactant. This procedure creates circular deposits with a diameter of approximately 0.50 cm for the Zn (anode) and Ag_2O (cathode) onto a 1.5 cm $\times$ 4.0 cm fabric cutout. This proof-of-concept diameter of the anode and cathode was chosen so as to allow the battery cell to fit onto the defined fabric cutout while also enabling hand-stitching of E-threads across the deposits to serve as current collectors. In this particular case, flexible Cu/Ni E-threads

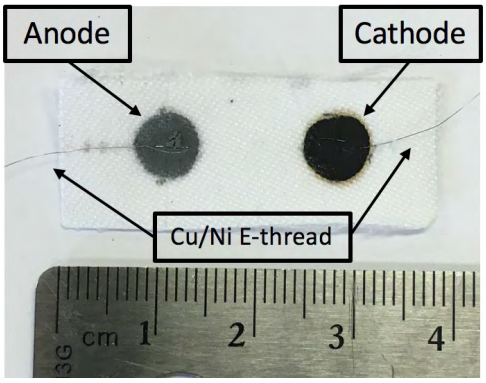

FIGURE 2. Printed battery cell consisting of Silver Oxide (cathode) and Zinc (anode) deposited onto a flexible fabric.

of 0.075mm diameter [26] are selected for electrical probing. Fig. 2 shows a completed, flexible printed battery cell on a polyester fabric.

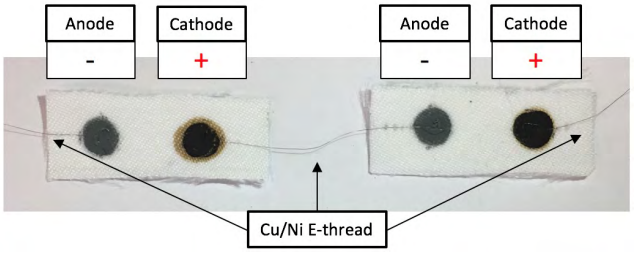

FIGURE 3. Two printed battery cell consisting of silver oxide (cathode) and zinc (anode) wired in series using Cu/Ni E-threads.

B. FABRICATION OF INTER-CONNECTED BATTERY CELLS

To allow for DC power scalability, multiple printed battery cells can be inter-connected in series or parallel, or combinations thereof depending on the desired current and voltage output. For example, a voltage boost can be achieved by connecting two or more of the printed battery cells in series. To do so, flexible electrically conducting threads can be stitched into the polyester fabric in order to electrically measure and utilize the energy stored in these battery cells. As an example, Fig. 3 shows the physical representation of two printed battery cells in a series arrangement. In this particular case, two battery cells were printed on two separate pieces of polyester fabric, and flexible Cu/Ni E-thread was used to stitch/connect these cells for maximum electrical contact. Each of the cells were, eventually, moistened separately. Alternatively, instead of physically separating the two cells, hydrophobic sprays (or other means of electrical separation) could be employed between adjacent battery cells to avoid detrimental short circuits. Expectedly, similar techniques can be pursued to wire the printed battery cells in a parallel arrangement, per the application requirements.

IV. MEASUREMENT RESULTS

A. POWER GENERATION FROM A SINGLE CELL

The power generation capabilities of our in-house fabricated electrochemical fabrics were measured using standard

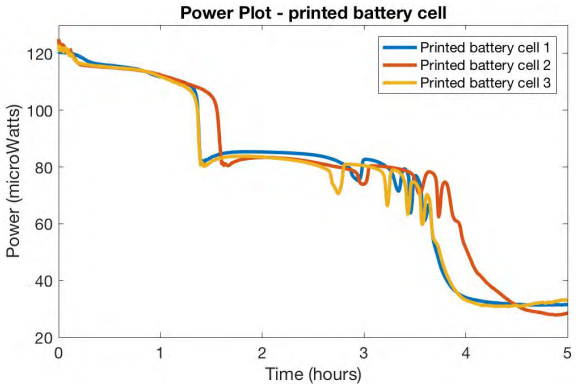

FIGURE 4. Power discharge curve of the printed battery cells.

electrochemistry techniques. To obtain the discharge characteristic of the printed battery cells, galvanostatic measurements (constant cell discharge) were performed that helped evaluate the voltage performance and capacity available.

As a proof-of-concept, a conventional electrolyte for an alkaline Ag_2O/Zn battery, 10 M NaOH, was used to establish the discharge characteristics of the batteries printed on fabrics. A constant discharge current of 100 μA was applied to a single pair of anode and cathode while the voltage of the cell was measured. Fig. 4 shows a variation of the galvanostatic data gathered, where power instead of voltage is plotted on the y-axis, thereby showing the available power versus time from a single printed battery cell at a constant 100 μA load. The results from three separate battery cells are super-imposed, demonstrating consistency, and, thus, verifying the reproducibility of the designed electrochemical cells on the fabrics. Notably, Fig. 4 can be evaluated in three parts: the first hour, hours 2-4, and hours 4-5. In the first hour, the power generated by the printed battery cell starts at approximately 120 μW and falls to $\sim$100 μW. Then, at around the 80-minute mark, the first depletion region occurs and the battery cell stabilizes to $\sim$80 μW for 3 hours. Finally, a second depletion region occurs at the end of the fourth hour, and the battery cell stabilizes at $\sim$30 μW.

B. POWER SCALABILITY

Table I shows the voltage boost achieved by connecting multiple printed battery cells in a series arrangement (see Fig. 3). As shown, a single cell in 10 M NaOH generates 1.46 V, whereas the voltage is boosted to 2.54 V when two cells are connected in series, and to 2.85 V when three cells are

TABLE 1. Scalability results.

Number of 'printed' battery cells in series	0.5 M NaCl saline solution	DPBS Buffer solution	10 M NaOH solution
1	0.96 V	0.97 V	1.46 V
2	1.52 V	1.76 V	2.54 V
3	2.07 V	2.41 V	2.85 V

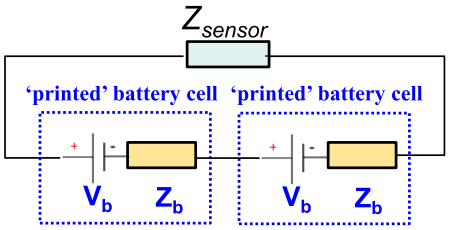

FIGURE 5. Equivalent circuit model for two printed battery cells in series arrangement.

connected in series. Similar voltage scaling is observed when using DPBS buffer (mimicking wound fluid) and 0.5 M saline solution (mimicking human sweat) as the electrolyte. Since DPBS and saline are weaker electrolytes compared to 10 M NaOH, lower voltage levels are generated by the printed battery cell.

As seen, and contrary to conventional batteries, the voltage boost from the batteries printed on fabrics is not linear. This non-linearity is due to the high built-in impedance associated with the printed battery cell. To better understand this non-linearity, Fig. 5 shows an equivalent circuit model for two printed battery cells connected in series, while (3) shows how to calculate a potential voltage boost when the battery cells are connected to a sensor.

$$V_{sensor} = 2V_b \frac{Z_{sensor}}{2Z_b + Z_{sensor}} \tag{3}$$

Here, V_b is the voltage generated by each of the printed battery cells, Z_b is their built-in impedance, and Z_{sensor} is the impedance of a sensor device to be powered via the proposed configuration. For a conventional battery, Z_b is orders of magnitude less than Z_{sensor}, so the Z_b term in (3) is negligible and linear voltage scaling occurs. However, the built-in impedance of the printed battery cell is not negligible compared to a typical sensor impedance (e.g., $Z_{sensor} = 120\ k\Omega$ for the digital thermometer to be employed in Section IV.C); therefore, non-linear voltage scaling occurs. This high value for Z_b is attributed to a range of factors, ranging from the exact geometry of the metal deposits on the fabric to possible impurities in the metals used to make the metal slurries.

C. PROOF-OF-CONCEPT DEMONSTRATION OF POWERING UP A THERMOMETER

A proof-of-concept experiment was performed to demonstrate powering of a digital thermometer using the proposed printed batteries on fabrics. To do so, an Anpro thermometer was employed. The minimum operational voltage and current requirements for this device were measured to be 1.5 V and 12.5 μA, respectively. Under these conditions, the impedance of the thermometer was calculated to be 120 kΩ. According to Table I, the voltage level produced by a single printed battery cell was not enough to consistently power on the sensor. Hence, two printed battery cells wired in a series arrangement were used to meet the sensor power requirements.

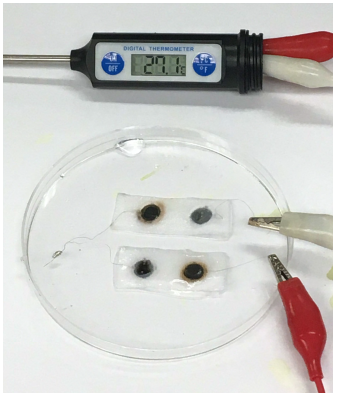

FIGURE 6. Two printed Zn/Ag_2O battery cells deposited onto a flexible fabric, wired in series using thin Cu/Ni E-thread and soaked in 10M NaOH, powering a digital thermometer.

Our proof-of-concept experimental set-up is shown in Fig. 6. Specifically, the employed printed battery cells were fabricated based on the process described in Section III.A, connected via conductive E-threads as shown in Fig. 3, and further moistened by: a) a conventional 10 M NaOH solution, b) a buffer solution (mimicking human body fluid) and c) a saline solution (mimicking human sweat). In all three cases, and as shown in Fig. 6, the power levels were high enough to successfully power the digital thermometer.

To our knowledge, this is the first time that powering of sensor electronics is demonstrated using flexible batteries printed on fabrics with biological fluid mimics.

V. CONCLUSION

We introduced a novel method for powering wearable electronics by integrating electrochemical storage onto fabrics. Contrary to conventional powering techniques (batteries, RF power harvesting, etc.), the designed method leverages conductive liquids readily available on the body (sweat, wound fluid, etc.), and is fully flexible, behaving like regular clothing. Proof-of-concept results for a single battery cell demonstrated sustained power generation of ~80 μW. Importantly, multiple of these printed battery cells can be inter-connected to scale the DC power, hence, allowing flexibility in meeting various application/sensor requirements. As an example, a series combination of two battery cells inter-connected via flexible E-threads was shown to successfully power up a digital thermometer.

Scalable DC power up to the mW range and for long periods of time is envisioned for the future, to be realized via optimization of the associated materials, pattern design, internal impedance characteristics, and inter-connections. Overall, this novel technology is expected to be vital for unobtrusively powering electronics in military, sports, and emergency operations, among others.

ACKNOWLEDGMENT

(Ramandeep Vilkhu and Wesley Joo-Chen Thio contributed equally to this work.)

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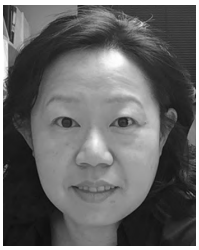

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Dr. Kiourti has received several awards and scholarships, including the URSI Young Scientist Award in 2018, the IEEE Engineering in Medicine and Biology Society Young Investigator Award for 2014, the IEEE Microwave Theory and Techniques Society Graduate Fellowship for Medical Applications for 2012, and the IEEE Antennas and Propagation Society Doctoral Research Award for 2011. She is currently serving as an Associate Editor for the IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION.