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Screen Printed Flexible Water Activated Battery on Woven Cotton Textile as a Power Supply for E-Textile Applications

YI LI[1], SHENG YONG[1], NICHOLAS HILLIER[2], SASIKUMAR ARUMUGAM[1,3], AND STEVE BEEBY[1], (Senior Member, IEEE)

[1]Smart Electronic Materials and Systems (SEMS), School of Electronics and Computers Science, University of Southampton, Southampton SO17 1BJ, U.K.
[2]EPSRC Centre for Doctorial Training in Energy Storage and its Applications, University of Southampton, Southampton SO17 1BJ, U.K.
[3]Organic Chemistry Synthesis, Catalysis and Flow Group, School of Chemistry, University of Southampton, Southampton SO17 1BJ, U.K.

Corresponding authors: Yi Li (yi.li@soton.ac.uk) and Sasikumar Arumugam (s.arumugam@soton.ac.uk)

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ABSTRACT Electronic textiles (e-textiles) development has been attracting significant research interest over the past two decades, especially in the field of wearable electronics. Fabric based flexible batteries are an attractive solution to the challenge of powering e-textiles. This work presents a simple and scalable textile primary battery, produced via a low-cost screen-printing manufacturing process. The device architecture is purposefully simple, based on a standard aluminum-silver redox reaction and a salt bridge. The battery as manufactured is inactive and requires the addition of water to be activated, and it can therefore be classified as a reserve battery. The battery is suitable for long-term storage, having negligible self-discharge rates. Initial batteries achieved a total area capacity of 101.6 μAh/cm^2 and an energy density of 2.178 mWh/cm^3 above 0.8 V. Further refinements of the battery include the inclusion of a novel membrane separator within the woven cotton textile layer and blending the metal salts with polyvinyl alcohol to reduce the number of textile layers. This optimization resulted in an improved performance of 166.8 μAh/cm^2 in area capacity and 3.686 mWh/cm^3 in energy density above 0.8 V. This work has demonstrated the feasibility of an aluminum-silver reserve textile battery and demonstrates a novel method for printing a phase inversion membrane separator into the textile. Following an encapsulation process, this flexible textile battery can be easily integrated into a standard woven textile, providing a robust, lightweight and flexible power supply.

INDEX TERMS E-textiles, flexible battery, phase inversion membrane separator, primary battery, textile battery, water activated battery.

I. INTRODUCTION

In the previous two decades, research on the topic of electronic textiles (e-textiles) has made substantial progress [1]–[3]. A significant quantity of this research concerns wearable applications in both military and domestic applications, focusing on body energy harvesting [4], consumer electronics [5], [6]. Other non-wearable applications include architectural and the creative industries [7]. This has attracted many commercial companies' interest [8], [9] towards commercialization, for example, Google developed capacitive touching textiles, called Google Jacquard [10]. The Google Jacquard is used in Adidas products for football players by connecting the physical activity and digital gaming. The Google Jacquard is further used by Levi's trucker jacket to answer calls, play music and take photos from the sleeve. Again, the same technology is also used by the fashion designer, Saint Laurent, on its backpack to control music, drop pins on the go, take pictures, all with a simple gesture. Philips developed Lumalive, a light emitting fabric pre-2010 [11], which has since been developed into interior space lighting system by ColorKinetics [12].

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One important application of e-textiles is human healthcare monitoring [13], for example, skin-adhering electrodes to detect the bio-signals in electroencephalography measurements [14]. Alongside the electronic aspects of e-textiles, the power supply for these electronics is a significant challenge and a key limitation for the practical application to the technology. Integrating power supplies in textiles has implications for health and safety, long-term stability, shelf life, flexibility, wash-ability, replacement/recharging and sustainability. Conventional approaches to powering e-textile applications are to use standard off-the-shelf capacitors and batteries, for example, coin cells [15] and AA/AAA batteries [16]. However, these off-the-shelf power supplies are rigid, bulky and are incompatible with the natural wear-ability of the fabric, restricting the flexibility of the garment and being obtrusive for the wearer [17]. Research activities exploring the integration of energy storage into the textile include both flexible textile supercapacitors [18], [19] and flexible textile batteries [20], [21]. Both above approaches can be incorporated into the textile or built up on the fabric surface to provide energy storage capacity while maintaining the textile properties. However, the self-discharge of these devices and the incorporation of liquid and gel aqueous electrolyte remain a challenge for the practical, safe and sustainable deployment of e-textiles.

Textile battery fabrication can be achieved by two different pathways: (1) A conductive yarn (or conductive material coated natural fiber) is used to fabricate a yarn-based battery [21], which then can be subsequently woven into the textile. (2) A commercially available woven textile product or lab prepared conductive woven textile is used as the substrate to carry the subsequently deposited functional layers on either one or both sides of the textile [22], to form the textile battery. Comparing both approaches, yarn-based batteries have a very limited area energy capacity due to the intrinsic yarn dimension and poses a challenge to scalability due to the complicated integration steps to form the e-textile Directly depositing the battery material on top of the existing textiles benefits from a much simpler production methodology and offers easily scalable, large area, devices with greater energy capabilities. It also results in higher area capacity and avoiding the complicated textile integration. Therefore, the yarn-based battery approach is not of interest for this study.

Fabrication of textile battery with existing woven textiles remains a significant challenge, due to the woven textile intrinsic properties, for examples, porosity, flexibility, surface energy and surface roughness. Therefore, to date, fabrication of textile battery with existing woven textile has met with limited success. Gaikwad *et al.* [23] demonstrated an early version of the textile battery based on manganese and zinc, with an open circuit voltage of 1.5 V and an area capacity of 3.875 mAh/cm^2. However, the textile can only be considered as a carrier of the conductive electrode materials, housed inside an elastomer casing, filled by polymer gel electrolyte. The actual practicality towards textile battery for wearable or other e-textile application is extremely limited. Chang *et al.* [22] reported a textile secondary lithium sulfur battery with high area capacity of 3 mAh/cm^2 and energy density of 360 Wh/L. Jian's method, however, requires commercially available membrane and lithium foil. The fabrication also involved several complicated deposition procedures and device assembly inside an inert atmosphere. Willert *et al.* [24] reported a printed battery on technical textile, which was pre-coated with poly(vinyl chloride) (PVC) and polyurethane (PU). The zinc manganese battery reached 3 V with an area capacity of 3 mAh/cm^2 at a discharge current of 200 μA and a cut off voltage of 0.9 V. The PVC based textile battery showed a lower average discharge voltage, but a higher area capacity compared to the PU based textile battery. However, the same fabrication solution cannot be widely used on the standard woven textiles without pre-coated surface. Ha *et al.* [25] demonstrated a lithium ion battery on a conductive carbon textile, which also acted as the current collector. The battery achieved an area capacity of 1.2 mAh/cm^2. The battery demonstrated stable open circuit voltage retention under repeated bending (1000 cycles) around a radius of 10 mm. however, it is worth to point out here, a commercially available membrane separator is used in this battery fabrication. In addition, lithium ion battery remains the environmental and health and safety concerns.

Water activated batteries have a long history and were first invented in the 1940s for applications requiring low temperature, high discharge current and high capacity, for example, torpedoes [26]. This battery type has been widely used as a power source for air rescue equipment and life jackets [26]. Aquapower [27] has successfully commercialized a water activated rechargeable 1.5 V AA battery, which can power flashlights, mini lanterns and portable radios. In large-scale high-power applications, Magnevolt [28] has developed a water activated battery which has been used by the United States Armed Forces since 1986. Figure 1 (a) shows a magnesium cuprous chloride water activated battery from Magnevolt [28] and (b) shows water activated battery in use in a survivor locator light [28]. Once it is immersed in the seawater the battery will be activated which can power an emergency light for 8 hours. Ferrerira *et al.* [29] reported a moisture activated paper battery made by sandwiching together paper with evaporated copper and aluminum metal layers, which achieved an output voltage of 0.7 V and the current density of 0.5 mA/cm^2. Lee [30], [31] reported a urine activated paper battery, achieved maximum voltage of 1.47 V and maximum power output of 1.5 mW over a 1 k Ω load resistor. The urine activated paper battery was constructed as a planar structure with each functional layer stacked up on top of the plastic substrate.

The first water activated batteries realized on a textile substrate was reported in 2015 [32]. Liu and Lillehoj [32] reported a liquid activated textile battery, achieving voltage of 1.3 V, which could be used for the detection of aqueous liquid, powering an LED upon detection. It was fabricated by stacking up several dip coated textile layers, as shown in Figure 2. In 2018, Vilkhu *et al.* [33] reported a textile

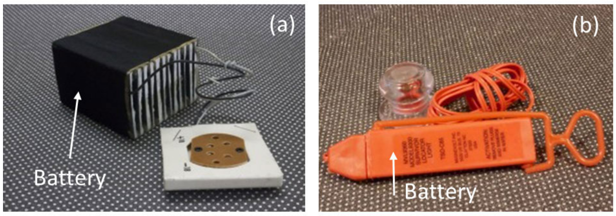

FIGURE 1. **(a) Magnevolt magnesium cuprous chloride water activated batteries are primarily used by government agencies in meteorological applications [27], and (b) Magnevolt survivor locator lights with the built-in water activated battery, which can be triggered by immersing in seawater and producing a power of light for 8 hours [27].**

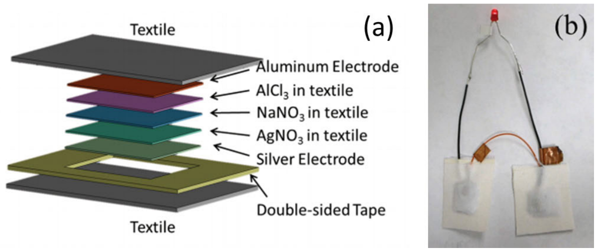

FIGURE 2. **(a) Schematic illustration of the textile battery including each functional layers and textile packaging, and (b) A two-cell textile water activated battery connected in series to a LED after activation using 20 μL of di-ionized (D.I.) water. (a,b) Reproduced under the terms of the Creative Commons Attribution 3.0 License (CC BY 3.0). (https://creativecommons.org/licenses/by/3.0/). [31] Copyright 2015, IOP Publishing.**

primary battery printed on a polyester textile, achieving an open voltage of 1.46 V with a sustained power of $\sim 80\ \mu$W. However, the testing was done by soaking the two textile electrodes into a high concentration 10M NaOH solution. It is a proof of concept work, which did not lead to an assembled or encapsulated battery cell. In 2019, the author [34] presented the preliminary result of this research work without the novelty of the phase inversion membrane, achieving total power output 70 μAh above 1 V and 225 μAh above 0.5 V. At the time, 4 different functional layers were dip coated with an additional aluminum pad. In 2020, Vališevskis *et al.* [35] reported a liquid activated textile primary battery, composed of various conductive metal wire meshes and conductive textiles. The best test result achieved an open circuit voltage of 0.69 V and a short circuit current of 41.5 mA, by using the conductive textile - Shieldex ®Budapest. The best result achieved is not promising compared to the previous reported [32], [34].

In this paper, we detail the design and development of a textile primary battery and propose manufacturing the electrochemically active elements in a dry form, requiring the addition of water to activate the battery. Without the addition of water, the battery remains inactive indefinitely. The fabrication is carried out directly onto a commercially available woven cotton textile and utilizes a simple manufacturing process that is compatible with existing textile processes. This provides a route to scalability, and potentially wide-spread adoption of the technology. The work starts by explaining the two half redox equations of the battery based on the electrode pair of silver (Ag) and aluminum (Al). The functional materials used, and the novel fabrication process is then described. The fabrication process advances water activated batteries through reducing the number of textile layers by introducing a built-in separator membrane. This approach enables the separator membrane to act as the virtual textile layer that contains the metal oxide salt reducing the number of textile layers and reducing the battery thickness. The testing regime, results and discussion are then presented. Finally, the conclusion highlights the outcome of this research work and its potential for use in real world application.

II. DESIGN AND FABRICATION

The water activated primary battery is an aluminum-silver (Al-Ag) electrochemical cell providing a theoretical potential difference of 2.46 V. A full Al-Ag electrochemical cell consists of two half-cells connected with a salt bridge. Aluminum - aluminum chloride (Al-$AlCl_3$) form the first half cell and the second is silver-silver nitrate (Ag/$AgNO_3$). Cotton impregnated with sodium nitrate ($NaNO_3$) acts as the salt bridge to maintain the electrical neutrality between the two half-cells. The reaction can be explained equations (1) and (2), respectively.

$$Al \rightarrow Al^{3+} + 3e^{-} \tag{1}$$

$$Ag^{+} + e^{-} \rightarrow Ag \tag{2}$$

The first type of water activated primary battery evaluated in this work (denoted Type 1) consisted of four functional flexible cotton layers with an aluminum foil electrode (Product number: 408-9574, supplied by RS Components) as battery cathode. The aluminum foil electrode has thickness of 90 μm. The standard 100% pure cotton woven textile has thickness of $\sim$500 μm, fiber diameter of 19 μm, weight density of 69.8 mg/cm^2, supplied by Fabric Land Southampton, UK. The battery cathode was a cotton electrode which was screen printed with conductive silver paste (Dupont 5000, supplied by Dupont), which was then cured in a conventional oven for 15 minutes at 150° C. Three pieces of cotton electrode were dip coated in silver nitrate ($AgNO_3$, Mw $\sim$ 169.87, product number: 209139, supplied by Sigma Aldrich) solution in de-ionized (D.I.) water, aluminum chloride ($AlCl_3$, Mw $\sim$ 133.34, product number: 294713, supplied by Sigma Aldrich) solution in D.I. water and sodium nitrate ($NaNO_3$, Mw $\sim$ 84.99, product number: S8170, supplied by Sigma Aldrich) $NaNO_3$ solution D.I. water with molar concertation of 2M, 6M and 3M, respectively. The dip coating process was carried out in an ultrasonic bath to enhance the homogeneously coating around the yarns. These dip coated cotton textile layers were cured under vacuum at room temperature for 24 hours to avoid any salt decomposition. It is also noted here that, all of the metal salt coated textile and the electrode layers can be prefabricated and stored in a vacuum desiccator for future use. All five layers were then cut into a circular shape with diameter of 1 cm. These four layers are

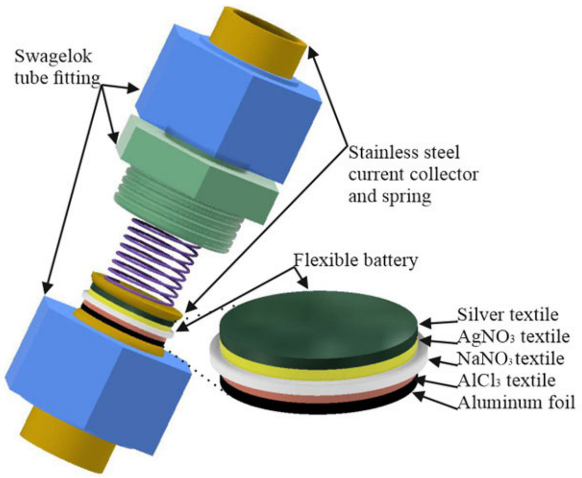

FIGURE 3. Illustrative figure of the Swagelok ®tube fitting, which is used to assemble the water activated textile battery (Type 1) for energy discharging measurement.

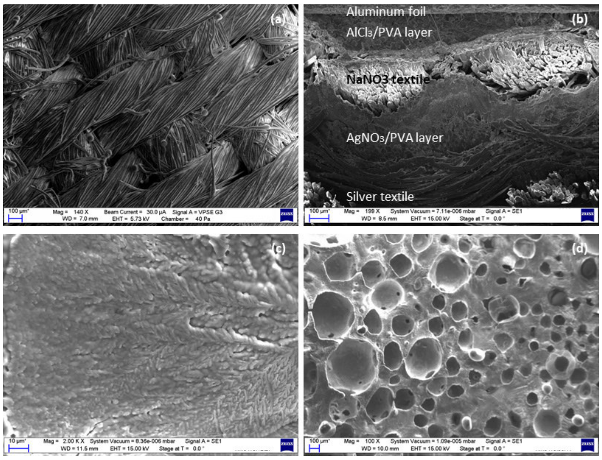

FIGURE 4. (a) Plane view of the standard woven cotton textile without any chemical treatment or functional material coating. Cross sectional view SEM images of (b) flexible water activated textile battery - Type 2, (c) enlarged view of $AgNO_3$/PVA layer under high magnification, and (d) enlarged view of the porous $AlCl_3$/PVA layer under high margination.

the four functional textile layer that form the water activated battery. Figure 3 shows the schematic diagram of the five layers before assembly with a Swagelock ®testing tube. The four functional cotton layers and the aluminum foil electrode were sandwiched in the tube fitting for testing purposes. The tube fitting holds and compresses the layers with a force of 0.5 Newton supplied by the stainless-steel spring. In order to activate the battery, 0.2 mL D.I. water was added into the tubular test cell at the time of testing. However, the design and assembly of the Type 1 battery results in an inflexible battery due to the combined thickness of four thick cotton textile layers. In addition, the cell cannot be well encapsulated, via hot pressing technique, due to the thickness of the battery.

The second type of the water activated primary battery evaluated (Type 2) consists of two functional cotton layers with an aluminum foil electrode as the battery anode. The battery cathode and anode were the same as for the Type 1. In the Type 2 battery, $AgNO_3$ and $AlCl_3$ were dissolved in a polyvinyl alcohol (PVA)/D.I. water gel (1:10 by wt%). The molar concentration of $AgNO_3$ and $AlCl_3$ was maintained the same as for the Type 1. The $AgNO_3$/PVA and $AlCl_3$/PVA gels were screen printed on top of the silver epoxy coated cotton cathode and aluminum foil anode respectively using a semi-automatic screen printer (DEK 248). The material coated anode and cathode were immersed in acetone and sonicated for 2 minutes until two separated porous PVA/$AgNO_3$ and PVA/$AlCl_3$ membranes were formed. The coated anode and cathode layer were then dried in vacuum at room temperature for 2 hours until all acetone and water were fully evaporated. Finally, the anode and cathode layers were cut into circular discs with a diameter of 1 cm. The salt bridge was prepared by adding 0.2 mL $NaNO_3$ solutions in D.I. water with a molar concertation of 3M on top the cotton textile with a circular diameter of ∼1.2 cm. The salt bridge layer has a larger diameter that the other layers in order to minimize the leakage current and prevent short circuits. The salt bridge layer was dried under vacuum at room temperature for 2 hours until all the water fully evaporated. As shown in figure 4 (a), the scanning electron microscopic (SEM) image of the plan view of the standard woven cotton textile, without pre-treatment for the fabrication of the textile battery. Figure 4 (b) shows the cross-section view of fabricated flexible battery showing the top aluminum foil anode, $AlCl_3$/PVA dried polymer layer, $NaNO_3$/cotton textile separator layer, $AgNO_3$/PVA dried polymer layer and silver coated cotton cathode. The two PVA blended metal salt layers demonstrated a thickness of less than 200 μm. The total effective cell thickness without the two metal electrodes is around 500 μm. The entire battery has an effective surface area of 0.785 cm^2 with radius of $\sim$ 10 mm. Figure 4 (c) and (d) shows the cross-sectional SEM image of the $AgNO_3$/PVA and $AlCl_3$/PVA dried polymer layer respectively. The combination of screen-printing and phase inversion process was used to create a porous and rough $AgNO_3$ and PVA composite layer. In addition, the same set of processes were also used to produce a porous $AlCl_3$/PVA layer with micro pores of between 50 and 200 μ m in diameters. These porous PVA structures significantly improve the contact area between the two half-cells (Al/$AlCl_3$, Ag/$AgNO_3$).

The water activated primary battery (Type 2), as shown in Figure 5(a), was encapsulated by ethylene-vinyl acetate (EVA) polymer films using a heat pressing process. Figure 5(b) shows the schematic illustration of the functional layers in its cross section. It creates a discrete flexible battery that does not require the tube fitting for testing. This encapsulation process can be easily deployed and is scalable. Before the encapsulation stage a hole with diameter of 0.25 cm was punched on the EVA film at the center of the cotton anode electrodes. This hole is designated as the inlet of the 0.2 mL of D.I. water into the cotton layer that holds the dry $NaNO_3$ salt. Therefore, the dissolved $NaNO_3$ salt is rehydrated by the D.I. water and creates the salt bridge between the battery's anode/cathode layer, which activates

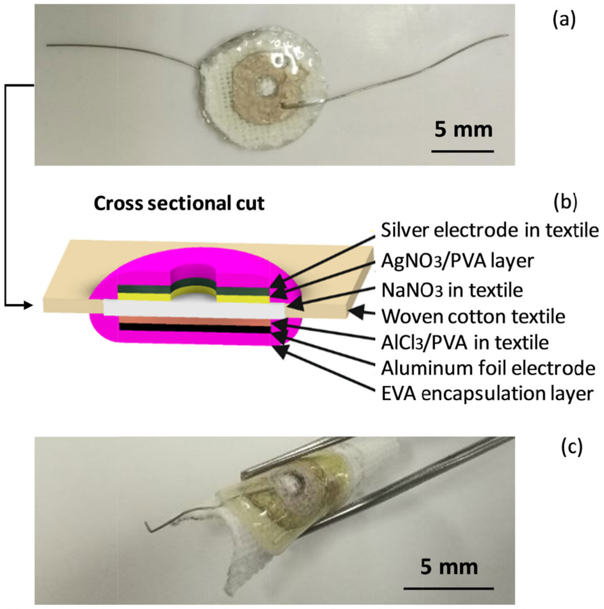

FIGURE 5. **Photograph of the water activated battery (Type 2) on textile with an additional schematic illustration of the water activated battery (Type 2) on textile with each layers' annotation.**

the battery. It is also noted here, while the battery remains dry it can be stored without significant energy discharge. This has been tested in this research work, with the final device characteristics showing little difference. Devices made 2 months and 2 weeks before the final test performed in a comparable set of results.

III. RESULT AND DISCUSSION

The discharge characteristics of the water activated primary batteries were measured and evaluated using a Autolab Pgsatat101 (Metrohm Autolab, The Netherlands). The electrical capacity of water activated primary batteries (both Type 1 and Type 2) were characterized by a galvanostatic discharge method with the Autolab Phsata101 equipment. The discharging current was set to be 0.5 mA/cm^2. The discharge current is equivalent to 0.395 mA. Then the measured battery cells' area capacity can be obtained by dividing the current capacity by the effective cell area. The energy density can be obtained by dividing the total energy above 0.8 V by the volume of the functional membranes without the two electrodes. Figure 6 (a) and (b) show the battery galvanostatic discharge result of the water activated primary batteries (Type 1 and Type 2).

Both types of batteries demonstrated an initial voltage of over 1.2 V after activation by the addition of the D.I. water. The discrete flexible battery (Type 2) achieved a higher output area capacity of 166.8 μAh/cm^2 above 0.8 V than the 101.6 μAh/cm^2 obtained from the Type 1 battery encapsulated in the Swagelock ®tube fitting. At the same time, the Type 2 battery also achieved a higher energy density (2.178 mWh/cm^3) than Type 1 battery (3.686 mWh/cm^3). This can be explained by the $AgNO_3$/PVA and $AlCl_3$/PVA dried polymer layers in the Type 2 device being thinner and more porous than the cotton textile that contains the dry $AgNO_3$ and $AlCl_3$ salt in the Type 1 device. The Type 2 battery with the porous metal salt layers also has a larger total area where the oxidation/reduction reaction occurs, leading to the increase in the total capacity. The blended PVA/salt layer improves the battery capacity, while also reducing the device thickness for subsequent encapsulation processes. In the Type 2 battery, the reduced number of textile layers

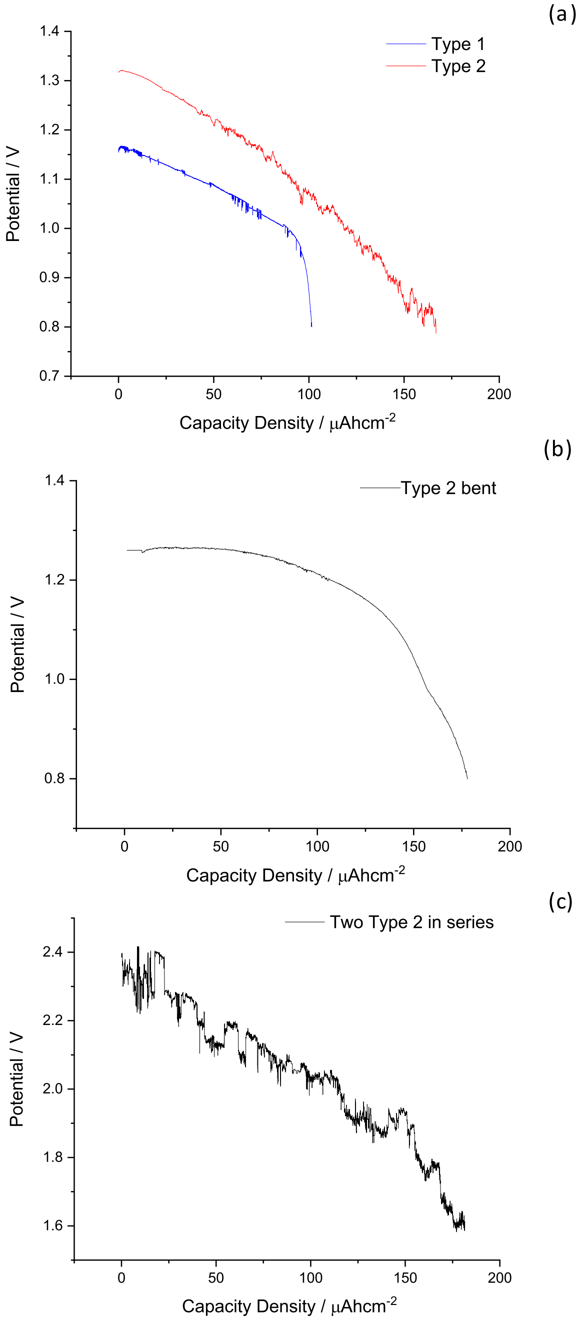

FIGURE 6. **(a) Voltage discharge results of the original (Type 1) and enhanced (Type 2) battery after activated with 0.2ml of de-ionized water, (b) Voltage discharge results of the bent outwards Type 2 flexible battery after activated with 0.2ml of de-ionized water, and (c) Voltage discharge results of the two Type 2 flexible batteries connected in series after activated with 0.2 ml of de-ionized water.**

TABLE 1. Summary table of the four batteries discharging measurement with two different type batteries under different testing condition.

Battery type	No. of Textile layers	Encapsulation	Flexibility	Starting voltage, V	Area capacity*, μAh/cm^2	Energy density**, mWh/cm^3
Type 1	5	N	N	1.18	101.6	2.178
Type 2	2	Y	Y	1.32	166.8	3.686
Type 2 bent	2	Y	Y	1.26	177.9	-
Two Type 2	2	Y	Y	2.40	181.5	-

*Area capacity (μAh/cm^2) is only taken account of the current discharged above 0.8 V.

**Energy density (μWh/cm^3) is only taken account of the energy discharged above 0.8 V.

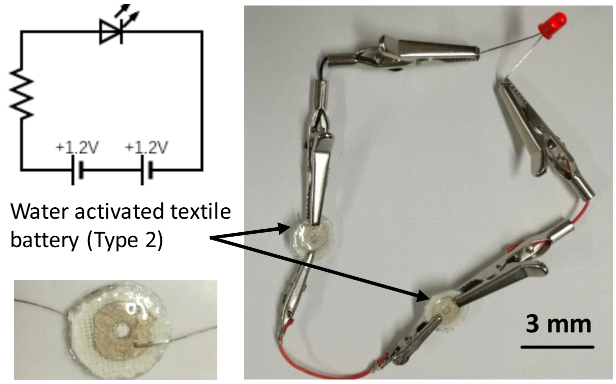

FIGURE 7. **Two flexible water activated textile battery (Type 2) connected in series powering a red colored light emitting diode (LED). Additional (i). illustrative circuit diagram is added to support the testing set up; (ii). an enlarged encapsulated water activated textile battery is shown under the annotation.**

makes the hot-pressing encapsulation process more practical, resulting in a discrete battery that is more flexible than the four textiles layered Type 1 battery.

The flexibility of the Type 2 water activated primary battery is shown in Figure 5(c). In Figure 6 (c), the discharge measurement was carried out while the battery is being bent 90 degrees outwards. Bending the flexible textile battery means the device experiencing tension and the compression forces on the textiles throughout the functional layers. Figure 6 (c) demonstrates higher output mean area capacity of 177.9 μAh/cm^2 above 0.8 V than the flattened Type 2 battery, area capacity of 166.8 μAh/cm^2. The bending test was carried out with five battery cells and the mean value is obtained by averaging the five sets of measurement. Both Type 1 and Type 2 batteries were tested under the same testing parameters. The difference in the measured capacity can be explained by the following statement. When the battery cell is under bent condition, the tension force from the outward bending forces a closer contact between each functional layer across the effective electrochemical cell. This reduced layers' thickness forces the electrolyte (D.I. water with $NaNO_3$) to penetrate the two electrodes to achieve a higher capacity, via $Al/AlCl_3$ and $Ag/AgNO_3$ pathways, respectively. It is clear to evidence that the fabricated water activated textile primary battery in this research work achieved higher performance in the area capacity, compared to the previous reported literatures on the same research topic of the water activated textile primary battery [31]–[34].

Figure 7 shows upon activation a battery pack with two Type 2 batteries connected in series can successfully power a red LED. The two non-bent Type 2 batteries demonstrated an initial voltage of 2.38 V, as shown in Figure 6 (c). The battery pack achieved an output area capacity of 181.5 μAh/cm^2 above 0.8 V. As shown in figure 7, this battery pack can light up a 5 mm red LED (Kingbright L-53ID, supplied from RS Components). This type of LED has a maximum power consumption value of 105 mW and a typical forward voltage of 2 V. In this LED power up test, the battery pack had successfully powered the red LED continuously for 20 minutes before battery pack voltage dropped below 2 V. Table 1 summarizes the four discharge measurement made with the textile batteries, their physical properties and their electrical parameters derived from the same measurement.

IV. CONCLUSION

This paper demonstrates a novel and straightforward fabrication method of a water activated textile battery. The novel phase inverted separator membrane, reported in this paper, shows a promising result and electrical performance within a battery, compared to the battery without it. The Type 1 battery with four textiles layers' battery was made then sealed in the Swagelock® tube fitting while the Type 2 has an enhanced battery architecture that is built around the woven cotton textiles. The Type 2 battery has polymer-salt layers and is encapsulated in EVA films. The Type 2 battery also achieved significantly higher output than Type 1 battery in area capacity of 122.2 μAh/cm^2 compared with 89.1 μ Ah/cm^2, and energy density of 3686 mWh/cm^3 compared with 2178 mWh/cm^3. The proposed battery is fully flexible and scalable to achieve relatively high output voltages, which are important in e-textile applications. The result of Type 2 battery with reduced textile layers and the in-built phase-inverted separator membrane shows a significantly increased battery performance, in relation to discharging rate, capacity and area capacity. This reported fabrication method for textile batteries can be easily added to e-textile applications with maximal flexibility and indefinite shelf life prior to activation, which is highly desirable for emergency power supply applications.

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YI LI received the B.Eng. degree in electronic engineering from the University of Warwick, in 2008, the M.Sc. degree in micro-system technology (MST), in 2009, and the Ph.D. degree in printed electronic components for e-textile applications from the University of Southampton, U.K., in 2013. He is currently a Senior Research Fellow with the Smart Electronics and Material Group, School of Electronics and Computer Science, University of Southampton. His main current research interests include functional material formulation investigation and developing e-textile applications in printed e-textiles, such as solar cells, light emitting devices, and smart bandages.

SHENG YONG received the B.Eng. degree in electrical and electronic engineering from the Imperial College London, in 2011, the M.Sc. degree in micro electromechanical systems (MEMS) in 2012, and the Ph.D. degree in fabrication and characterization of fabric super capacitor from the University of Southampton, U.K., in 2017. He is currently a Research Fellow with the Smart Electronics and Material Group, School of Electronics and Computer Science, University of Southampton. His current research interests include functional material formulation for e-textile, developing energy storage device for printed e-textiles, such as super capacitor, primary and secondary batteries, and hybrid battery-super capacitor energy storage device.

NICHOLAS HILLIER received the Master of Physics (M.phys.) degree from the University of Southampton, in 2013, where he is currently pursuing the Ph.D. degree with the Energy Storage and its Applications Centre for Doctoral Training. His current research interests include power management of e-textiles, specifically looking to integrate super capacitors, and batteries directly into textile.

SASIKUMAR ARUMUGAM received the bachelor's degree, in 2005, and the master's degree in chemistry from the Bishop Heber College, India, in 2007. He has been a Research Fellow with the Smart Electronic Materials and Systems Group, School of Electronics and Computer Science, University of Southampton, U.K., since 2013. He is currently with the School of Chemistry, University of Southampton, on synthesizing novel molecules for light emitting electrochemical cells on colour changing e-textile applications. His research interests include printed textile solar cells and light emitting devices on e-textiles. He received the Scottish Overseas Research Award Scheme to pursue the Ph.D. degree in chemistry from the University of Strathclyde, U.K., in 2010.

STEVE BEEBY (Senior Member, IEEE) received the B.Eng. degree (Hons.) in mechanical engineering from the University of Portsmouth, Portsmouth, U.K., in 1992, and the Ph.D. degree in MEMS resonant sensors from the University of Southampton, Southampton, U.K., in 1998.

He was a Co-Founder with Perpetuum Ltd., Southampton, a university spin-out based on vibration energy harvesting, in 2004. He was also with Smart Fabric Inks Ltd., Southampton, and D4 Technology Ltd., Southampton. He is currently the Head of the Smart Electronic Materials and Systems (SEMS) Research Group, School of Electronics and Computers Science, University of Southampton and he also leads the U.K.'s E-Textiles Network. He also leads three U.K.-funded research projects. He received over 16 million research funding. He has coauthored or edited four books, including Energy Harvesting for Autonomous Systems (Artech House), in 2010. He has given 25 invited talks and over 300 publications. He holds over ten patents. He has an H-index of 52. His current research interests include energy harvesting, e-textiles, and use of energy harvesting in wearable applications.

Dr. Beeby was a recipient of two prestigious EPSRC Research Fellowships to investigate the combination of screen-printed active materials with micro machined structures and textiles for energy harvesting. He also received the Personal Chair in 2011. He serves as the Chair of the International Steering Committee for the PowerMEMS Conference Series.

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