Development and characterization of textile batteries

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Abstract. During the past years, smart textiles have gained more and more attention. Products cover a broad range of possible applications, from fashion items such as LED garments to sensory shirts detecting vital signs to clothes with included electrical stimulation of muscles. For all electrical or electronic features included in garments, a power supply is needed – which is usually the bottleneck in the development of smart textiles, since common power supplies are not flexible and often not lightweight, prohibiting their unobtrusive integration in electronic textiles. In a recent project, textile-based batteries are developed. For this, metallized woven fabrics (e.g. copper, zinc, or silver) are used in combinations with carbon fabrics. The article gives an overview of our recent advances in optimizing power storage capacity and durability of the textile batteries by tailoring the gel-electrolyte. The gel-electrolyte is modified with respect to thickness and electrolyte concentration; additionally, the influence of additives on the long-time stability of the batteries is examined.

1. Introduction

Smart textiles have increasingly attracted interest in recent years by textile designers and technologists. Since they often contain electronic components, most of them need a power supply.

Electric energy can be stored in textiles using common rigid batteries or capacitors. However, due to the limitations imposed by integrated hard objects on textile fabrics in terms of haptics, drape or bendability, several approaches have been made to develop flexible textile-based energy sources. Besides textile capacitors and pseudo-capacitors, textile batteries are often investigated [1]. Capacitors and batteries can be created by layer systems coated on textile substrates [2] or in fiber-shape, the latter capable of being integrated into woven or knitted fabrics [3-5]. While early approaches concentrated, e.g., on silver electrodes combined with PEDOT as an electrolyte [6] to build rechargeable textile batteries, other researchers showed the advantage of carbon nanotubes as electrode material [7] or used similar materials as in common rigid batteries, such as lithium-iron-phosphate and lithium titanate [5].

Such textile batteries, however, usually lack the required energy densities and lifetimes. Additionally, as well-known from various research initiatives in the area of smart textiles, results can often not be reproduced with the necessary reliability. This is why the recent project focuses on studying the influence of electrolyte thickness and concentration as well as the electrode materials as a base for further optimization of 2D textile batteries.
2. Experimental

A battery consists at least of two electrodes produced from different materials, separated by an electrolyte. The voltage between the electrodes depends on the difference between their redox potentials as given by the Nernst equation as well as secondary effects like over-potentials. This voltage is triggered by a redox reaction in the electrolyte with different partial reactions near both electrodes. A current can flow when these areas are electrically connected.

Different metals can be combined as electrode pairs; however, the difference between their normal potentials should be high to enable high voltages between them. Some examples of normal potentials are $E_{0,Cu} = 0.34 \text{ V}$ for copper, $E_{0,Ag} = 0.79 \text{ V}$ for silver, and $E_{0,Ni} = -0.23 \text{ V}$ for nickel [8], showing that the combination of silver and nickel can result in higher voltage drops than copper-nickel cells. Interestingly, carbon has also shown to be an interesting partner in combination with copper or nickel electrodes. As carbon will not take place in the redox reaction, it will only act as a pick-up electrode for a possible redox reaction in the electrolyte itself [9]. In this research, copper coated polyester woven fabrics, marketed under the name “copper ripstop fabric” (Less EMF Inc.), silver coated polyamide fabrics, called “Shieldex® Zell” (Statex), and a carbon nonwoven fabric, type HP-U100/50C (HP-Textiles), are utilized.

As electrolyte, iodine-triiodide is used in the form of mixture of iodine and potassium iodide with a concentration of 5% iodine in aqueous solution. Iodine-triiodide has proven to be more efficient than metal salts, such as copper sulphate or nickel sulphate [10].

This electrolyte can be used to form a gel-like electrolyte to decrease evaporation and drying which would result in a reduced ion conductivity of the electrolyte (Fig. 1). For the gel-electrodes, commercially available gelatine was mixed with the aqueous solution of iodine/potassium iodide at a temperature of 60°C using a stirrer. In the description of the single experiments, the iodine concentration in the aqueous solution is given, ranging from 0.25% to 1.0%. It was not possible to form uniform gelatine-gels with higher electrolyte concentration.

Electrolyte layers were produced using a squeegee or hand roller with 500 µm wet film thickness. The resulting dry film thicknesses are slightly increased.

Measurements are performed using adequate multimeters and a resistance decade to allow taking complete I-V-curves.

3. Results

Fig. 2 depicts I-V-curves and P-V-curves of silver-carbon batteries with 0.75% iodine in form of a gel. Different numbers of gel-electrolyte layers were introduced between both electrodes, resulting in different maximum voltages and currents. The maximum powers gained from these batteries increase with increasing gel-electrolyte thickness. This may be an indication for redox activity inside the electrolyte.

It should be mentioned, however, that increasing the electrolyte thickness is limited due to the increasing bending stiffness of the resulting textile battery. Thus, other parameters should also be taken into account to increase the battery power. Additionally, the increase of voltage and current with increasing electrolyte layer thickness is lower for higher gel-electrolyte thicknesses.
Figure 2. I-V-curves (left panel) and P-V-curves (right panel) of silver-carbon batteries with different gel-electrolyte layer thicknesses. All values are averaged over 5 batteries.

Figure 3. Open-circuit voltages and short-circuit currents, measured for different concentrations of iodine/triiodide in the gel of thickness 0.5 mm for copper-carbon and silver-carbon batteries. All values are averaged over 5 batteries.

In Fig. 3, the open-circuit voltages and short-circuit currents for battery series with different parameters are depicted. The open-circuit voltages measured on copper-carbon batteries saturate around 0.5 % iodine in the aqueous solution, while for silver-carbon batteries, a higher concentration of 1.0 % iodine is necessary to reach higher voltages. The short-circuit current is increased for higher iodine-triiodide concentrations for both electrode combinations. Nevertheless, it must be mentioned that the partly large error bars indicate instabilities in the battery performance. While measured current values stabilize with increasing iodine-triiodide concentrations, the opposite effect is visible for the short-circuit currents. Apparently, a compromise must be found to create textile batteries with reliable performance.

Furthermore, increasing the amount of iodine-triiodide is limited to the values used in this research. Higher concentrations of the electrolyte in the gel resulted in severe problems during gelling, making the layer mechanically instable.

The electrode potential of the cells is mainly influenced by the iodide concentration, since it is linked to the solubility product of AgI:

\[ E = E_0 + \frac{RT}{F} \ln[^{\text{Ag}^+}] \]

\[ K_I = [^{\text{Ag}^+}] \cdot [^{\text{I}^-}] \]

\[ E = E_0 + \frac{RT}{F} \ln \left( \frac{K_I}{^{\text{I}^-}} \right) \]
with $K$: solubility Product, $[A]$: activity of species $A$, $E_0$: standard potential, $R$: gas constant, $T$: absolute temperature, and $F$: Faraday constant.

However, as depicted in Fig.2, the available amount of iodine has significant influence on the electric charge, delivered by the system. This gives rise to the idea that iodine also contributes to the electrochemical reaction. Therefore an oxidation of the metal electrodes by iodine can be proposed, but the system is limited by the solubility of the metal iodides.

4. Conclusion
To conclude, we have shown that textile batteries can be created using metalized or metallic electrodes, combined with a carbon electrode. As the electrolyte between both electrodes, iodine-triiodide was used which is quite common in flexible and textile solar cells, as well as batteries.

Gelling this electrolyte results in flexible, bendable textile batteries which can even be used without further treatment for short times, while long-term stability necessitates either encapsulation or addition of stabilizing agents.

Future research will focus on further electrolyte materials and different possibilities to solidify them as well as other electrode materials forming iodides of higher solubility.

5. References
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