International Journal of Clothing Science and Technology

The electric energy stored in PEDOT:PSS capacitors integrated on textile substrate: Limits and possibilities

Sheilla Atieno Odhiambo, Piotr Fiszer, Gilbert De Mey, Carla Hertleer, Ida Nuramdhani, Lieva Van Langenhove, Andrzej Napieralski,

The electric energy stored in PEDOT:PSS capacitors integrated on textile substrate

Limits and possibilities

Received 21 December 2017
Accepted 1 August 2018

Sheilla Atieno Odhiambo, Piotr Fiszer, Gilbert De Mey, Carla Hertleer, Ida Nuramdhani, Lieva Van Langenhove and Andrzej Napieralski
(Information about the authors can be found at the end of this article.)

Abstract

Purpose – The purpose of this paper is to develop a capacitor fully integrated into a wearable textile fabric for the application on smart clothing.

Design/methodology/approach – A small capacitor with stainless steel yarns as the electrodes and poly-(3,4–ethylenedioxythiophene): polystryrene sulphonate (PEDOT:PSS) as the dielectric material has been made, integrated into a textile fabric. The electric performance of the capacitor was analyzed and compared with other kinds of electric capacitors.

Findings – The fabricated small, PEDOT:PSS capacitor could finally power a calculator for 37 s with the energy stored in it.

Originality/value – This finding is of an important significance for a further development on the capacitor with a better performance.

Keywords PEDOT:PSS, Stainless steel conductive yarns, Textile capacitor

Paper type Research paper

1. Introduction

The main goal of this research is to develop a capacitor which is fully integrated into a wearable textile fabric. Such a device is used to design the so-called smart clothing (Van Langenhove and Hertleer, 2004). Besides capacitors, resistors and other electric and electronic components have been developed as well by other researchers. It must be emphasized here that the integration of these components into textiles is the most challenging part of this research.

In this contribution, a capacitor is made by sewing two stainless steel yarns into a polyester-cotton fabric. These yarns are the electrodes or the capacitor. poly-(3,4-ethylenedioxythiophene): polystryrene sulfonate (PEDOT:PSS) is used as the dielectric material. Starting from a liquid solution, small quantities of the PEDOT:PSS polymer are dropped onto the fabric in a small area (6–10 mm) where the distance between the two stainless steel yarns is no more than 1 or 2 mm. After drying, the device is ready for use.

Depending on the ratio between PEDOT and PSS, the electric conductivity can change a lot (Akerfeldt *et al.*, 2013a, b). Usually, papers dealing with PEDOT:PSS use the good conducting mixture. One will also observe that PEDOT:PSS is mainly used as the electrode material to make a good contact with other materials (Laforgue, 2011). In this contribution, the low conducting PEDOT:PSS is used as the dielectric material between two stainless steel yarns electrodes in order to make a capacitor, being able to store electric energy for a limited time.

Sheilla Atieno Odhiambo, on leave from the Moi University, Eldoret, Kenya, wants to thank the VLIR (Flemish Interuniversity Council) for the financial support for her stay at the University of Ghent. Piotr Fiszer thanks the EU for the financial support for his stay at the University of Ghent within the framework of the Erasmus Student Exchange Programme. Ida Nuramdhani wants to thank the Research Council of the Ghent University for her PhD fellowship.

International Journal of Clothing Science and Technology
Vol. 30 No. 6, 2018
pp. 808-816
© Emerald Publishing Limited
0955-6222
DOI 10.1108/IJCST-12-2017-0190

2. Charge discharge measurement and discharge characteristics

The PEDOT:PSS capacitors are charged with the circuit shown in Figure 1. By closing the switch S, the PEDOT:PSS is charged with a constant voltage V_0 (1.5, …, 3 V in our experiments). The time-dependent voltage $v(t)$ across the PEDOT:PSS cell is also recorded with a voltage meter (VM), having a high input resistance of 10 MΩ. After a sufficient charging time (normally 2 h), the switch S is opened and the PEDOT:PSS cell starts to discharge across the VM. Eventually, an additional load device can be connected in parallel to the VM.

Typical discharge characteristics of devices after charging at a constant voltage $V_0 = 3$ V are shown in Figure 2. Curves A and B were obtained after 2 h and 40 min charging, respectively. Curve C was also obtained after 40 min charging but with PEDOT:PSS cell connected to a calculator. Similar results have been published elsewhere as well (Bhattacharya *et al.*, 2009; Odhiambo *et al.*, 2014; Odhiambo, Mey and Hertleer, 2014). In the beginning, the voltage decays very rapidly from 3 V to a value around 1.5 V. Then the voltage decay still continues but much slower. For a complete discharge, several hours are needed.

From the results shown in Figure 2, it is obvious that the PEDOT:PSS cells are lossy capacitors. A perfect capacitor connected to a VM will also show a decaying voltage due to the discharge across the input resistance of 10 MΩ. Such a discharge curve is always an exponential function. The experimental observed curves in Figure 2 cannot be fitted to exponential decaying functions. This experiment proves that the PEDOT:PSS do not behave like a classical capacitance. Nevertheless, it is very useful if we can attribute a capacitance value to the PEDOT:PSS cell in order to make a comparison with commercially available capacitors.

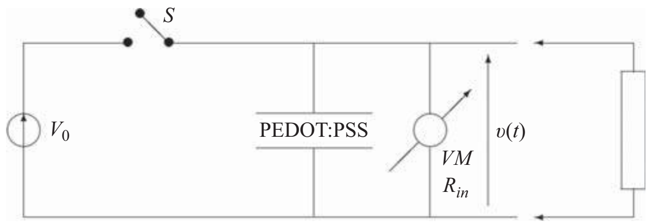
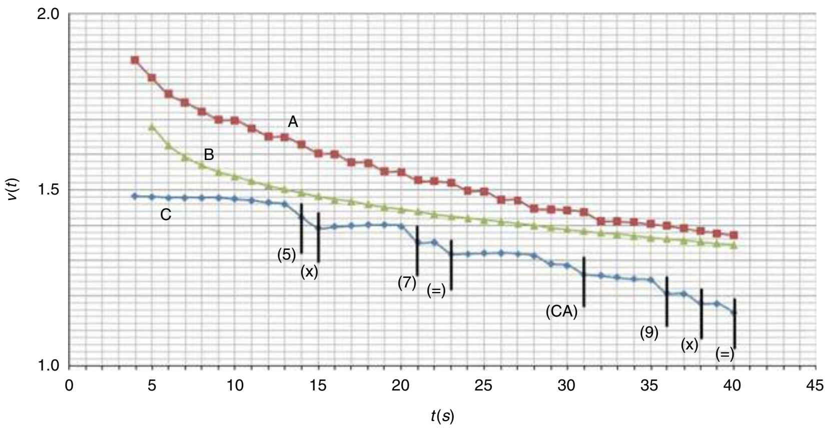


Figure 1. Schematic layout of the charge discharge measurements



Notes: A: 2 h charging; B: 40 min charging; C: 40 min charging with the PEDOT:PSS cell connected to a calculator

Figure 2. Several discharge curves of PEDOT:PSS cells

Due to the long-time constants involved in the transient characteristic, it is not possible to use a simple capacity meter to characterize the cells. Therefore, we evaluate the electric energy supplied to the VM:

$$E_{el} = \int_{t_{ini}}^{\infty} \frac{v^2(t)}{R_{in}} dt = \int_{t_{ini}}^{\infty} p_{el}(t) dt, \tag{1}$$

where $p_{el}(t) = v^2/R_{in}$ is the instantaneous electric power delivered to the VM. Obviously p_{el} is the product of the voltage v and the current v/R_{in}. The moment t_{ini} corresponds to the opening of the switch S ($t_{ini} = 2$ h in the case of Figure 3). The integral (1) has been evaluated numerically using the trapezoidal rule (Abramowith, 1970). The result was found to be:

$$E_{el} = 0.8101 \text{ mJ} = 0.22\ \mu\text{Wh}. \tag{2}$$

The numerical quadrature was carried out from $t_{ini} = 7{,}200$ s to 19,800 s (approximately 5.5 h) because the measurement was stopped at 19,800 s.

The amount of energy can be attributed to an equivalent capacitance C_{eq} charged to 3 V, storing the same amount of energy:

$$\frac{1}{2} C_{eq} V_0^2 = E_{el} = 0.8101\ mJ = 0.22\ \mu\text{Wh}. \tag{3}$$

From which we get:

$$C_{eq} = \frac{2E_{el}}{V_0^2} = 180\ \mu\text{F}, \tag{4}$$

which is a rather high value comparable to electrolytic capacitors with similar dimensions. But the value (4) is much less as compared to the present-day supercapacitors.

The decay characteristic of PEDOT:PSS cells can be quite well fitted to the following mathematical function:

$$V_0 e^{t/\tau} erfc\left(\sqrt{\frac{t}{\tau}}\right), \tag{5}$$

where τ is a time constant and erfc the complementary error function. In (5), $t = 0$ is the initial moment of the voltage decay. From the fitting of (5) with the experimental results, we

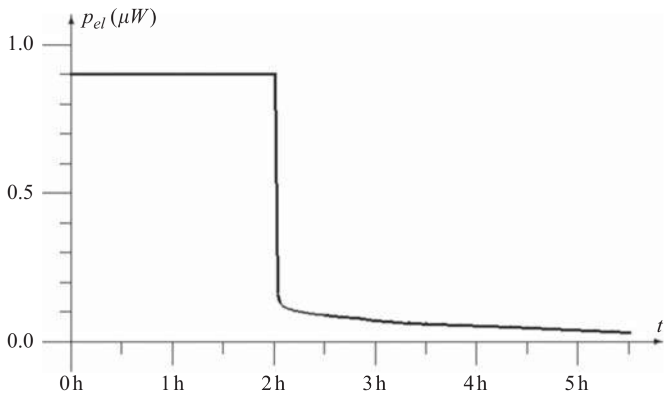


Figure 3.
Delivered power as a function of time

obtain the value $\tau = 3{,}600$ s. As shown in Figure 1, the PEDOT:PSS cell is loaded with a resistor of $R_{in} = 10\,\mathrm{M\Omega}$ (the input impedance of the VM). A classical capacitor C_{RC} in combination with the same load resistor R_{in} giving rise to the same time constant τ should have the value:

$$C_{RC} = \frac{\tau}{R_{in}} = \frac{3{,}600}{10^7} = 360\,\mu\mathrm{F}. \tag{6}$$

It should be remarked here that the discharge characteristic of a classical capacitor is exactly an exponential function exp $(-t/\tau)$, which is quite different from (5). Strictly speaking Equation (6) is only valid for an exponential decay. As a consequence, the value (6) for C_{RC} is twice the value (4) we obtained for C_{eq}. This difference is rather small taking into account that two totally different methods have been used to obtain the results (4) and (6). Last but not least, the PEDOT:PSS material does not behave as a classical dielectric, i.e., with a constant dielectric constant. These capacitance values are just used to compare our PEDOT: PSS cells with commercially available capacitors.

3. Characterization of the PEDOT:PSS cells: Ragone plot

In this section, our cells were compared with other capacitors available on the market and research centers. First of all, a Ragone plot will be presented. Then our cells will be characterized using the capacitance per unit weight, per unit area and per unit volume.

The Ragone plot presents the power density in W/kg vs the energy density in Wh/kg for all kinds of capacitors (Figure 4). The plot shows regions for capacitors, supercapacitors, batteries and even fuel cells. In order to compare our PEDOT:PSS cell with the actual capacitor market, we have to evaluate the performance of our PEDOT:PSS cells in terms of power density and energy density.

The electric energy in a PEDOT:PSS cell was measured to be $E_{el} = 0.8101$ mJ $= 0.22$ μWh. In the experiment with the calculator, which will be outlined further on, it was found that the PEDOT:PSS cells were able to power a calculator for 37 s. This corresponds to a power delivery P_{el} given by:

$$P_{el} = \frac{E_{el}}{37s} = 0.02189\,\mathrm{mW}. \tag{7}$$

The active area of the PEDOT:SS cell is $6\times10 = 60\,\mathrm{mm}^2$. From some of these cells, the active area was cut out and the weight was about $W_{CELL} = 0.168$ g. Note that this value includes

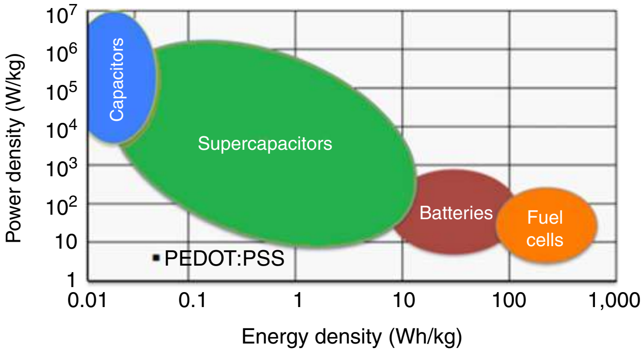


Figure 4. Ragone plot comparing the PEDOT:PSS cell with actual capacitors

the fabric, the PEDOT:PSS and the stainless steel electrodes. The stored energy per unit weight is then:

$$\frac{E_{el}}{W_{CELL}} = \frac{0.22}{0.168}\frac{\mu\text{Wh}}{\text{g}} = 1.309\frac{m\text{Wh}}{\text{kg}}, \tag{8}$$

$$\frac{P_{el}}{W_{CELL}} = \frac{0.02189}{0.168}\frac{\text{mW}}{\text{g}} = 0.1302\frac{\text{W}}{\text{kg}}. \tag{9}$$

These values are quite small as compared to the values displayed in the Ragone plot (Figure 4).

If we take into account that the electric energy is only stored in the PEDOT:PSS material, it should be more convenient to use only the weight of it, just to have a fairer comparison with data from the literature. It must be emphasized that in our case, the package or the fabric has a thickness around 1 mm, much more than the active thickness of the PEDOT:PSS. The weight of the deposited PEDOT:PSS material was roughly measured to be $W_{PEDOT:PSS} = 5$ mg. The results (8) and (9) have then to be replaced by:

$$\frac{E_{el}}{W_{PEDOT:PSS}} = 0.044\frac{\text{Wh}}{\text{kg}}, \tag{10}$$

$$\frac{P_{el}}{W_{PEDOT:PSS}} = 4.37\frac{\text{W}}{\text{kg}}, \tag{11}$$

the point with coordinates (10) and (11) has been added to the Ragone plot (Figure 4). From the energy density point of view, our cells can be fitted in between a capacitor and a supercapacitor. From the power density point of view, the PEDOT:PSS cell have a low performance. As a consequence, these cells can only be applied for low current (i.e. low power) applications such as portable electronic devices.

A third way is to use the weight of the electrodes. The active part of the stainless steel electrodes is just 1 cm for each electrode. The weight of the stainless steel yarns was 250 g/1,000 m. From this, we come up with a weight $W_{ELECTRODES} = 5$ mg. Hence, the densities referred to the electrodes weight will also be given by (10) and (11).

A look at the Ragone plot shows that our PEDOT:PSS cells have performed less, but this is the price one has to pay because our cell is fully integrated into a textile structure. As a consequence of this, the two electrodes are positioned next to each other with a minimal distance of 1 mm to avoid short circuiting between them. Putting two flat electrodes on top of each other with only PEDOT:PSS in between would obviously give rise to much higher densities. This approach, which is the classical flat plate capacitor, is not at all compatible with textile technology.

4. Comparison with other PEDOT:PSS cells

It should be mentioned here that the stainless steel yarns are made from numerous fibers. Hence the surface is far from being smooth, which guarantees a good electrical contact with the deposited PEDOT:PSS. Just for comparison, we mention that for porous electrodes, providing a high contact area, a theoretical value in the range 100–140 mAh/*g* has been reported (Snook *et al.*, 2011). If 1 V is applied, this corresponds to 100–140 Wh/kg, which is almost in the region of the fuel cells in the Ragone plot (Figure 4).

A common criterion to compare capacitors is the capacitance per unit weight. If we use the value (4), then we obtain the following values for our cells:

$$\frac{C_{eq}}{W_{CELL}} = \frac{180}{0.168}\frac{\mu\mathrm{F}}{\mathrm{g}} = 1.07\frac{\mathrm{mF}}{\mathrm{g}}, \tag{12}$$

$$\frac{C_{eq}}{W_{PEDOT:PSS}} = \frac{180}{5}\frac{\mu\mathrm{F}}{\mathrm{mg}} = 36\frac{m\mathrm{F}}{\mathrm{g}}. \tag{13}$$

Chen *et al.* (2009) reported 198.2 F/g for PEDOT:PSS with multiwalled CNTs. Frackowiak *et al.* (2006) obtained capacitances ranging between 100 F/g and 330 F/g with three types of conducting polymers: polyaniline, polypyrrole and PEDOT in combination with CNTs. CNTs, PEDOT:PSS and MnO_2 nanocomposite electrodes were used by Sharma and Zhai (2009). A value as high as 375 F/g was obtained. Without PEDOT this value was reduced to 175 F/g and if only CNTs and MnO_2 were used, a much smaller value of 15 F/g was found.

Weng and Wu (2013) obtained a specific capacitance of 365 F per gram electrode. They also report 100 Wh per kg electrode at a power of 200 kW per kg electrode. This supercapacitor was made from PEDOT:PSS, graphite oxide as well as carbon nanotubes.

Another way of comparison is to evaluate the capacitance per unit area. Normally, area means the area of the electrodes in contact with the dielectric. To get a better view, we use both the area of the cell which is $S_{CELL} = 0.6\times 1\ \mathrm{cm}^2 = 0.6\ \mathrm{cm}^2$ and the electrode area $S_{YARN} = \pi\ 400\ \mu\mathrm{m}\times 1\ \mathrm{cm} = 0.125\ \mathrm{cm}^2$ where 400 μm is the yarn diameter:

$$\frac{C_{eq}}{S_{CELL}} = \frac{180}{0.6}\frac{\mu\mathrm{F}}{\mathrm{cm}^2} = 0.3\frac{\mathrm{mF}}{\mathrm{cm}^2}, \tag{14}$$

$$\frac{C_{eq}}{S_{YARN}} = \frac{180}{0.125}\frac{\mu\mathrm{F}}{\mathrm{cm}^2} = 1.44\frac{\mathrm{mF}}{\mathrm{cm}^2}. \tag{15}$$

Lv *et al.* (2012) mention 1.3 F/cm^2 with electrodes made from PEDOT, CNTs and MnO_2.

Finally, the specific capacitance per unit volume can be used for comparison. First of all, we use the volume of a cell with dimensions $V_{CELL} = 0.6\times 1\times 0.1\ \mathrm{cm}^3 = 0.06\ \mathrm{cm}^3$:

$$\frac{C_{eq}}{V_{CELL}} = \frac{180}{0.06}\frac{\mu\mathrm{F}}{\mathrm{cm}^3} = 3\frac{\mathrm{mF}}{\mathrm{cm}^3}. \tag{16}$$

In the literature, the volume of the electrode is often taken into account. Hence, we have $V_{YARN} = \pi 0.02^2 \times 1\ \mathrm{cm}^3 = 0.00125\ \mathrm{cm}^3$, which, therefore:

$$\frac{C_{eq}}{V_{YARN}} = \frac{180}{0.00125}\frac{\mu\mathrm{F}}{\mathrm{cm}^3} = 144\frac{\mathrm{mF}}{\mathrm{cm}^3}. \tag{17}$$

Ghaffari *et al.* (2013) used a mixture of PEDOT and CNTs as the active material for a supercapacitor with a volumetric capacitance of 3.9 F/cm^3. With coated and densified PEDOT, this number could be increased to 84.9 F/cm^3.

One obvious comment has to be added at the end of this section. Our PEDOT:PSS cells are less performed than the results cited from the literature. But it must be mentioned again that we limit ourselves to textile technology. It means that only sewed yarns are used as electrodes and the PEDOT:PSS is deposited on the fabric by dropping and subsequent drying in an oven. Another difference is that in our case the

PEDOT:PSS was used as the dielectric material. In all the cited references, the PEDOT:PSS was used to improve the electrode materials in combination with CNTs and other materials. The only purpose of this approach is to make an electrode area with an enormous roughness so that the area in contact with the dielectric is huge. This realizes the high capacitance values.

5. Application: powering a calculator

As a demonstrator, a simple calculator has been powered by our PEDOT:PSS cells. The calculator has a liquid crystal display and is normally powered by built in photovoltaic cells. The four photovoltaic cells are connected in series to provide a supply voltage around 1.6 V and their global area is about $3.6\times0.9 = 3.24\,\text{cm}^2$. The calculator could operate quite well with the light from an incandescent lamp of $P = 60$ W at a distance of 1 m. Taking a typical light energy efficiency of $\eta = 5$ percent into account and assuming the light is uniformly spread over an area with radius $S = 1\,\text{m}^2$ we obtain the following light power density on the photovoltaic cells:

$$\frac{\eta P}{S} = 3\frac{\text{W}}{\text{m}^2}. \tag{18}$$

Assuming a typical efficiency of the photovoltaic cells of 10 percent, we get a power delivery of 972 μW. It must be emphasized here that this is only a very rough estimation. Therefore, the power consumption of the calculator was also measured by connecting it to a stabilized power supply of 1.63 V. The current was then 36.84 μA which gives us a power consumption of $P = 60\,\mu$W.

Obviously, during the following experiments the photovoltaic cells were covered with dark paper. It was verified that the calculator was no longer useable 1 s after the dark paper has been applied. This proves that all internal capacitors can be discharged in 1 s.

Using the electric energy E_{el} given by (2), we can estimate the time t that one PEDOT:PSS cell will be able to power the calculator:

$$t = \frac{E_{el}}{P} = \frac{0.8101}{60}\frac{\text{mJ}}{\mu\text{W}} = 13.5\text{ s}. \tag{19}$$

In our experiment, the calculator was powered by our two PEDOT:PSS cells connected in parallel. A picture of the setup is shown in Figure 5 and a schematic layout in Figure 6. By using two PEDOT:PSS cells, a time of use of 27 s could be expected. Experimentally the calculator could be used during 37 s. Two calculations could be performed with the PEDOT:PSS cells previously charged to 3 V.

Curve C in Figure 2 shows the discharge characteristic of a single PEDOT:PSS cell connected with the calculator after a 40-min charging at 3 V. One observes clearly that any time a button of the calculator was pressed, a sudden voltage drop appears. This is due to the fact that the electronic circuits are made with CMOS technology. CMOS transistor circuits consume almost no power when the input signals do not change. Power consumption only occurs when an input signal is varying, i.e. when the calculator is performing a calculation or a number is stored in the memory. The first calculation was "5×7 = ," and any time a button was pressed down (5 × 7 = CA 9 ×…) a clear voltage drop is observed as shown in Figure 2. As soon a constant number (35 in this case) is displayed and no buttons are pressed, the power consumption becomes negligible and the voltage decay is mainly due to the self-discharge of the PEDOT:PSS cell.

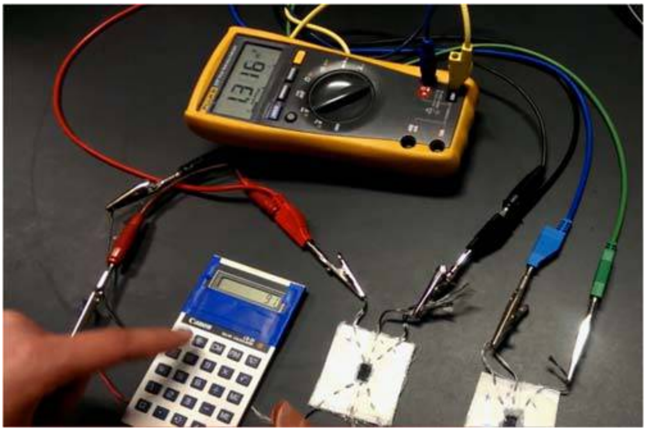


Figure 5. Photograph of the setup to power a calculator

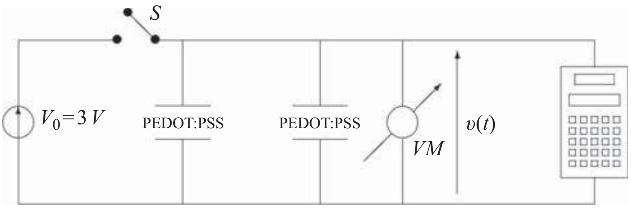


Figure 6. Schematic layout of two PEDOT:PSS cells in parallel powering a calculator

6. Conclusion

A capacitor has been made which is fully integrated and compatible with textile technology. Stainless steel yarns were used as the electrodes and PEDOT:PSS, dropped onto the fabric, as the dielectric materials. The performance of this device has been compared with commercially available capacitors as well as recent research on supercapacitors. As a demonstrator, it was possible to operate a simple calculator for 37 s using two PEDOT:PSS cells each with an area of only (6×10) mm^2.

References

Abramowith, M. (1970), *Handbook of Mathematical Functions*, Dover, New York, NY.

Akerfeldt, M., Straat, M. and Walkenstrom, P. (2013a), "Electrically conductive textile coating with a PEDOT:PSS dispersion and a polyurethane binder", *Textile Research Journal*, Vol. 83 No. 6, pp. 618-627.

Akerfeldt, M., Straat, M. and Walkenstrom, P. (2013b), "Influence of coating parameters on textile and electrical properties of a poly(3,4–ethylene dioxythiophene): poly(styrene sulfonate)/polyurethane coated textile", *Textile Research Journal*, Vol. 83 No. 20, pp. 2164-2176.

Bhattacharya, R., de Kok, M.M. and Zhou, J. (2009), "Rechargeable electronic textile battery", *Applied Physics Letters*, Vol. 95, e223305, doi: 10.1063/1.3269907.

Chen, L., Yuan, C., Dou, H., Gao, B., Chen, S. and Zhang, X. (2009), "Synthesis and electrochemical capacitance of core–shell poly (3,4–ethylenedioxythiophene)/poly (sodium 4-styrenesulfonate)-modified multiwalled carbon nanotube nanocomposites", *Electrochimica Acta*, Vol. 54 No. 8, pp. 2335-2341.

Frackowiak, E., Khomenko, V., Jurewicz, K., Lota, K. and Beguin, F. (2006), "Supercapacitors based on conducting polymers/nanotubes composites", *Journal of Power Sources*, Vol. 153 No. 2, pp. 413-418.

Ghaffari, M., Kosolwattana, S., Zhou, Y., Lachman, N., Lin, M., Bhattacharya, D., Gleason, K.K., Wardle, B.L. and Zhang, Q.M. (2013), "Hybrid supercapacitor materials from poly (3,4–ethylenedioxythiophene) conformally coated aligned carbon nanotubes", *Electrochimica Acta*, Vol. 112, pp. 522-528.

Laforgue, A. (2011), "All-textile flexible supercapacitors using electrospun poly(3,4–ethylene dioxythiphene) nanofibers", *Journal of Power Sources*, Vol. 196 No. 1, pp. 559-564.

Lv, P., Feng, Y.Y., Li, Y. and Feng, W. (2012), "Carbon fabric-aligned carbon nanotube/MnO_2/ conducting polymers ternary composite electrodes with high utilization and mass loading of MnO_2 for super-capacitors", *Journal of Power Sources*, Vol. 220, pp. 160-168.

Odhiambo, S., Mey, G.D. and Hertleer, C. (2014), "Reliability testing of PEDOT: PSS capacitors integrated into textile fabrics", *Eksploatacja i Niezawodność*, Vol. 16 No. 3, pp. 447-451.

Odhiambo, S.A., De Mey, G., Hertleer, C., Schwarz, A. and Van Langenhove, L. (2014), "Discharge characteristics of poly(3,4–ethylene dioxythiophene): poly(styrenesulfonate) (PEDOT:PSS) textile batteries; comparison of silver coated yarn electrode devices and pure stainless steel filament yarn electrode devices", *Textile Research Journal*, Vol. 84 No. 4, pp. 347-354.

Sharma, R. and Zhai, L. (2009), "Multiwall carbon nanotube supported poly(3,4–ethylenedioxythiophene)/ manganese oxide nano-composite electrode for super-capacitors", *Electrochimica Acta*, Vol. 54 No. 27, pp. 7148-7155.

Snook, G., Kao, P. and Best, A. (2011), "Conducting-polymer-based supercapacitor devices and electrodes", *Journal of Power Sources*, Vol. 196 No. 1, pp. 1-12.

Van Langenhove, L. and Hertleer, C. (2004), "Smart clothing: a new life", *International Journal of Clothing Science and Technology*, Vol. 16 Nos 1/2, pp. 63-72.

Weng, Y.-T. and Wu, N.-L. (2013), "High-performance poly(3,4–ethylene-dioxythiophene): polystyrenesulfonate conducting-polymer supercapacitor containing hetero-dimensional carbon additives", *Journal of Power Sources*, Vol. 238, pp. 69-73.

Author Affiliations

Sheilla Atieno Odhiambo, Department of Materials, Textiles and Chemical Engineering, Ghent University, Ghent, Belgium and Department of Manufacturing, Industrial and Textile Engineering, ACE II PTRE, Moi University, Eldoret, Kenya

Piotr Fiszer, Department of Microelectronics and Computer Science, Lodz University of Technology, Lodz, Poland and Department of Electronics and Information Systems, Ghent University, Ghent, Belgium

Gilbert De Mey, Department of Electronics and Information Systems, Ghent University, Ghent, Belgium

Carla Hertleer, Department of Materials, Textiles and Chemical Engineering, Ghent University, Ghent, Belgium

Ida Nuramdhani, Department of Materials, Textiles and Chemical Engineering, Ghent University, Ghent, Belgium and Department of Textile Chemistry, Politeknik STT Tekstil, Bandung, Indonesia

Lieva Van Langenhove, Department of Materials, Textiles and Chemical Engineering, Ghent University, Ghent, Belgium

Andrzej Napieralski, Department of Microelectronics and Computer Science, Lodz University of Technology, Lodz, Poland

Corresponding author
Ida Nuramdhani can be contacted at: Ida.Nuramdhani@UGent.be