Flexible textile power module

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Abstract. This paper reports the design, fabrication and testing of a flexible textile power module consisting of a ferroelectret energy harvester and solid-state supercapacitor energy storage device. Both devices can be combined and fabricated in a single woven textile layer. The textile ferroelectret achieved a peak power output of 0.47 μW.cm⁻² for a compressive force of around 350 N, and the single layer textile supercapacitor obtained an area capacitance of 5.2 mF.cm⁻². The ferroelectret can charge the textile supercapacitor via a full bridge rectifier to 48 mV in 40 seconds demonstrating the feasibility of combining these devices on the single textile.

1. Introduction
Electronic textiles (e-textiles), are a combination of electronic functionality and/or devices in a fabric. The powering of these devices is seen as a consistent challenge in the field of e-textiles [1], with flexibility of the power module being the significant hurdle. Typically, the electronic devices in e-textile system are powered by rigid batteries that require frequent charging or replacement [2]. Furthermore, these batteries are incompatible with the feel of the textile and, for example, washing processes. Therefore, a combination of textile based flexible energy harvester, energy storage and power management circuit could be a possible solution to power e-textiles.

Ferroelectret, or piezolectret, is a typically flexible and porous foams with voids filled with air. After polarization, electrical charge will be trapped at the interfaces around the void. When compressed, the flexible ferroelectret behave like a soft and sensitive piezoelectric material and produces an electrical signal [3]. It has been demonstrated that the porous foam can be replaced by a textile substrate sandwiched by polymer electret films making this type of ferroelectret highly suitable for use in wearable e-textile applications [4]. A textile supercapacitor is an electrochemical energy storage device with high power densities and a long cycle life. [5]. Supercapacitors can be fabricated into a single layer of textile using functional yarns or material coating techniques. This single layer contains the electrodes, electrolyte and charge separator in a single substrate [6]. In comparison with batteries, textile supercapacitors can avoid the use of hazardous substances such as acidic electrolytes and corrosive electrode materials making them suitable for wearable applications.

To date attempts to combine a textile supercapacitor and textile-based energy harvester together are based upon triboelectric nano-generators (TENGs) with a yarn supercapacitor that are made from both expensive carbonized materials such as carbon nanofibers and reduced graphene, and acidic gel
electrolyte. Dong et al. [7] reported a stretchable knitted textile power module produced from silicon rubber coated stainless steel/polyester fiber networks forming a TENG and a fiber supercapacitor with carbon nanofibers/poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS) fiber electrodes and an acidic gel electrolyte. This work generated an area power output of 1.6 μW.cm⁻² at 1 Hz with good capacitance. Pu et al. [8] presented a TENG fiber network made with nickel and parylene coated polyester straps, and a fiber supercapacitor fabricated from reduced graphene coated nickel yarn electrodes with an acidic gel electrolyte. These devices achieved an area power output of 3.3 μW.cm⁻² at 5 Hz and an areal capacitance of 72.1 mF.cm⁻². In both cases it is difficult to make a fair performance comparison since the standard metrics and yarns parameters (e.g. fiber shape, dimensions and resistance per unit length) are not consistently used. These works use bespoke fibers, acidic electrolytes and triboelectric harvesters realised from non-conventional textile materials.

This paper presents a power module for e-textiles by integrating a ferroelectret, supercapacitor and power management circuit within a single cotton substrate. The ferroelectret was made with fluorinated ethylene propylene (FEP) films sandwich. A solid-state supercapacitor was fabricated with spray coated carbon electrodes and a non-hazardous gel electrolyte made up with polyvinyl alcohol and Ammonium dihydrogen phosphate.

2. Device fabrication
A photograph of the textile power module is shown in figure 1. Four silver conductive tracks were screen printed using a silver paste (DuPont d 5000). The bridge rectifier chip was located at the centre of the silver tracks, with its chip pins punched through the cotton and bonded with silver epoxy to the printed silver tracks at the back of cotton textile.
Figure 1 (a) Photograph of textile power module, the scale bar is 10 cm. (b) Schematic of the ferroelectret structure showing the fabric sandwiched between the FEP films with the thin film aluminium electrodes and EVA seal. (c) Cross-sectional view of the single layer cotton supercapacitor, the scale bar is 200 µm.

Figure 1b shows the schematic of the FEP-cotton ferroelectret, which was fabricated using FEP films purchased from DuPont (304 mm × 200 mm × 25 µm). FEP films were cut into 70 mm × 70 mm square samples. An aluminium electrode of 60 mm × 60 mm × 100 nm was evaporated onto one side of FEP films (Bak600 Evaporator, Levbold Ltd.). The FEP-cotton ferroelectret was constructed by bonding the aluminium coated FEP film to each side of the cotton textile which had been impregnated with an Ethylene-vinyl acetate (EVA) polymer annulus. The FEP-cotton ferroelectret was polarized in a corona poling box with voltage of -20 kV for 60 seconds.

The top and bottom electrodes on the cotton were fabricated via spray coated carbon ink, that contains commercially available carbon powders (activated carbon powder Kuraray Yp-80F and carbon black powder Shawinigan Black), 1, 2, 4-Trichlorobenzene (1, 2, 4 TCB) solvent, a surfactant and EVA polymer binder. The cotton electrodes were vacuum impregnated with a gel electrolyte made with ammonium salt, vinyl-alcohol polymer and water. Finally the cotton electrodes containing the wet gel electrolyte were compressed and cured in oven for 2 hours at 40 °C. Figure 1c shows the SEM image of the textile supercapacitor device cross-section, both carbon electrodes were separated by cotton fibers leaving a gap that filled with the gel electrolyte.

The current connector layer is fabricated from silver, polyurethane and nickel. The silver and polyurethane were screen printed on top of a PDMS substrate, this layer was peeled off the PDMS after thermal curing. The nickel film was then spray coated on top of the silver to form an inert layer. The nickel ink was formed by mix up nickel powder (average size of 5 µm, from Sigma-Aldrich), Isoamyl acetate solvent and 1.2% by weight of EVA binder material. The electrical connector layers were used to connect the aluminium and supercapacitor to the printed silver tracks and the textile power module was sealed by a UV curable screen printed polyurethane layer.

3. Results and discussion

The piezoelectric charge constant d_{33} of the FEP-cotton ferroelectret was measured with a PiezoMeter (PM300, Piezotest Ltd). Its output profile was evaluated using an Instron electrodynamic instrument (ElectroPuls E1000, Instron Ltd). This applied a periodical square wave force of 350 N on the ferroelectret energy harvester samples at 1 Hz frequency.
**Figure 2.** FEP-textile ferroelectret output. (a) $d_{33}$ measurement. (b) Voltage output of FEP-cotton ferroelectret under cyclical 350 N compressive force with 10 MΩ load.

As shown in figure 2a the initial $d_{33}$ of the FEP-cotton ferroelectret was 520 pC.N$^{-1}$, it declined to 480 pC.N$^{-1}$ after 15 days after which is stabilises. Figure 2b shows the output voltage from FEP-cotton ferroelectret. Under the compressive force, the device generated a negative signal with peak voltage of -13 V with peak power of 16.9 µW and total energy output of 0.31 µJ. When the compression force was released, the device generated a positive signal with peak voltage of -3 V with peak power of 3.9 µW (0.11 µW.cm$^{-2}$) and total energy output of 0.13 µJ.

The electrochemical performance of the textile supercapacitor was tested using a VMP2 potentiostat/galvanostat (Biologic, France). The encapsulated supercapacitor was characterized by cyclic voltammetry (CV) at different scan rates and galvanostatic cycling (GC) at different scan currents.

**Figure 3** Electrochemical performance of the single layer cotton supercapacitor. (a) CV test results between +/- 0.8 V at scan rates of 200, 100, 50 mV s$^{-1}$. (b) GC derived area and volume capacitance (test current 1 to 5 mA.cm$^{-2}$), with a peak voltage of 0.8 V.

The CV results showed in figure 5a indicate the device is electrochemically stable but influenced by the resistance between the nickel film and the carbon electrode. The area capacity drops from 15 mF.cm$^{-2}$ to 9 mF.cm$^{-2}$ as the scan rate increases from 50 to 200 mV. In the GC tests, the textile supercapacitor exhibits area and volume capacitances of 5.2 mF.cm$^{-2}$ and 95 mF.cm$^{-3}$, with these values reducing as test current increases, as shown in figure 3b. When the area of the carbon electrode is considered (0.36 cm$^2$) the total capacitance was found to be 2 mF (based on the GC experiment).
Figure 4. Textile power module performance. (a) FEP-Textile ferroelectret charging an external 10 µF electrolytic capacitor. (b) FEP-Textile ferroelectret charging the 2 mF textile supercapacitor.

The energy storage performances shown in figure 4 were obtained from a human walking experiment where the textile module was placed under the shoe insole of a person whose weight was 70 kg. These experiments were undertaken with one step per second.

Figure 4a shows the 10 µF electrolytic capacitor was charged to 0.62 V in 40 steps. Given the capacitor was charged linearly in the first 40 steps the energy per mechanical step can be obtained with the total energy accumulated during the entire charging process of 1.92 µJ (0.048 µJ/steps). Under the same experimental setup, the 2 mF textile supercapacitor can be charged to 48 mV in 40 steps, with the energy stored equalling 2.3 µJ (0.057 µJ/steps). The textile supercapacitor can obtain higher energy than an electrolytic capacitor, which is attributed to the lower leakage of the textile supercapacitor compared to the electrolytic capacitor.

4. Conclusion
This work has demonstrated the feasibility of integrating a full power module in a single piece of cotton textile. The FEP-cotton ferroelectret can generate a peak power of 0.47 µW cm⁻² upon compression. The textile supercapacitor achieved an area capacitance of 5.2 mF cm⁻². The textile supercapacitor can be charged by the FEP-cotton ferroelectret via the rectifier circuit mounted on the same piece of cotton textile. Further work will include reducing the contact resistance between all the devices, to improve the power conditioning circuit efficiency and increase the energy converted from the mechanical motion. The final device could be adopted in a wide range of wearable electronic or e-textile systems.

5. References
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