WEARABLE AND WASHABLE PHOTOVOLTAIC FABRICS

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ABSTRACT: This work presents a novel solar energy harvesting fabric that can power wearable and mobile electronic devices in a robust, user-friendly, and sustainable manner. The fabric was realised by weaving miniature solar cell embedded textile yarns (solar-E-yarns) fabricated using the Electronic yarn (E-yarn) technology. The fabric (44.5 mm × 45.5 mm active area) can generate a maximum power density of 2.15 mW/cm² under one sun (1000 W/m²) solar illumination and looks and feels like a normal textile; it is soft, three dimensionally conformable, breathable and moisture absorbing. It is also capable of undergoing machine laundering, which has not previously been reported by a textile solar energy harvesting solution for wearable applications in the literature. The fabric can be rolled and is lightweight, making it desirable for mobile and off-the-grid energy needs.

Keywords: Photovoltaic, energy harvesting, wearable devices, electronic textile, E-textiles, solar cells

1 INTRODUCTION

Wearable and mobile electronic devices are playing an increasingly integral role in modern society thanks to advancements in the Internet of Things (IoT) and the miniaturization of electronic components: However, a challenge remains in how these devices can be powered in a robust, user friendly and sustainable manner. To keep these devices continuously powered without frequent recharging or bulky energy storage devices, many have proposed integration of energy harvesting capability into clothing.1,2

Solar energy harvesting has been one of the most investigated avenues for wearable applications due to the abundance of solar energy3 and maturity of photovoltaic (PV) technologies4. A number of fabrication techniques such as printing5, coating6 or laminating7 organic photovoltaics (OPVs)8 and thin film PVs9 onto textile substrates have been explored. Despite being inherently flexible, the monolithic film structure of these PV systems significantly changes the appearance and feel of the textile, as well as restricts its shear deformation and air permeability, making them uncomfortable and less appealing to the wearer. Fabrics woven with PV coated wires10 or flexible PV tapes11 show improvements in shear behaviour and breathability, however, they still look and feel significantly different from normal textile fabrics.

While most of the above textile-based PV systems are not compatible with water, few have demonstrated continuous PV functionality after exposure to detergent-water mixtures under mild conditions11,12. Which is far from the rigorous hydro-mechanical agitation undergone by regular clothing in a domestic washing machine. Additionally, the materials used in above systems have limited colour possibilities, which is also a key aesthetic element for consumers.

The solar fabrics were woven using solar-E-yarns that were created by embedding miniature crystalline silicon solar cells (SCs) within the core of a textile yarn by employing electronic yarn (E-yarn) technology13-17 invented at Nottingham Trent University, thus integrating the solar energy harvesting capability within the heart of the textile fabric. To achieve a drapable and soft fabric that can endure machine washing, the shear behaviour and low bending rigidity of the fabric structure had to be maintained. Therefore, in this work the rigid PV elements (solar cells) were deployed in a discontinuous fashion within the fabric in yarn form. The fibres of these textile yarns can take any colour.

The fabric demonstrated here (44.5 mm × 45.5 mm active area) was capable of continuously generating ~2.15 mW/cm² under one sun illumination and maintained both the feel and aesthetics of a normal textile. Solar fabrics can undergo domestic laundering and maintained ~90% of their original power output after 15 machine wash cycles. The solar fabric could charge various types of electricity storage devices such as lithium ion batteries, lithium-polymer batteries and supercapacitors, typically used in wearable devices.

Figure 1 - Cross sectional illustration of a solar-E-yarn.

2 MATERIALS AND METHODS

2.1 Fabricating of solar-E-yarns

Solar-E-yarn preparation involved three steps: First, ten 1.5 mm × 3 mm crystalline silicon SCs (Solar Capture Technologies, Blyth, UK) were soldered onto two fine copper wires (seven strand, linear density = 120 mg/m, single strand diameter = 50 μm, Knight Wire, Potters Bar, UK) parallel to each other with Pb-free solder paste (SolderPlus® S965D500A6, Nordson EFD, Dunstable, UK) using an infrared reflow soldering technique (PDR IR-E3 Rework System, PDR- Design & Manufacturing Centre, Crawley, UK). Gaps of 2 mm were maintained between adjacent SCs during the soldering process (Fig. 2(a)).

The soldered SCs along with a Vectran® carrier yarn (Vectran™, Kuraray America Inc., Houston, TX, USA) were then encapsulated within discrete cylindrical micro-pods, of a 1.6 mm diameter, made of ultra-violet curable acrylic resin (Dymax 9001E-V3.5 Dymax Corporation, Torrington, CT, USA). This hermetically sealed the SCs...
and interconnections. The length of each resin micro-pod (RMP) was maintained at approximately 4 mm. The encapsulation was conducted in such a way that the SC was positioned at the center of the RMP (Fig. 2(b)).

Finally, the strand of copper wires, Vectran® and RMP (hereafter referred to as solar-micro-pod filament) was covered by two sets of textile fibres using a knitting machine (RIUS MC-Knit braiders with 2.0 inner diameter hollow cylinders with six needles; RIUS, Barcelona, Spain). The first set of white texturized polyester (PET) fibres (made of four 48f/167 dtex yarns referred to as packing fibres) were delivered straight through the hollow needle cylinder and were distributed around the solar-micro-pod filament; thus, these did not form loops. The second set of white texturized PET yarns (six 48f/167 dtex yarns) were delivered to six knitting needles on the outer surface of the needle cylinder, which formed the warp knitted structure around the packing fibres, creating the final solar-E-yarn (Fig. 2(c)).

2.2 Preparation of solar cell embedded fabric

Twenty solar-E-yarns were woven into a fabric along with cotton yarns in the weft direction of the weave. The warp yarns used for the weave were also cotton. The woven structure was designed to provide maximum light exposure to the photoactive sides of the solar-E-yarns as illustrated in Fig. 3. After weaving the solar-E-yarns, two mini-modules were created by serially connecting the twenty solar-E-yarns (two serially connected sets of ten E-yarns). These two mini-modules were subsequently connected in parallel to realize the final solar-E-yarn network.

2.3 Characterization of solar-E-yarns and resultant fabrics.

The electrical characterization of solar-E-yarns and resultant fabrics were performed under one sun (AM 1.5 G spectrum, 1000 W/m²) irradiance using a LED solar simulator (LSH-7320 ABA LED solar simulator, Newport Corporation, CT 06615, USA). For I-V and P-V curve generation a network of fixed resistors that could be set to resistance values between 1Ω to 100MΩ was employed. The electrical measurements were conducted using a high precision digital multimeter (34410A 6 ½, Agilent Technologies LDA UK Limited, Stockport, UK). The temperature of the test samples was maintained at 25±2°C using a closed loop temperature control system equipped with a Peltier cooler, a cooling fan, and the thermocouple (Fig. 4).

The solar-E-yarns were machine washed in fabric form (BS EN ISO 6330:2012; Textiles — Domestic washing and drying procedures for textile testing) and line dried for 25 cycles. Similarly, a hand-washing test (AACTCC Monograph M5 for Standardization of Hand Laundering for Fabrics and Apparel) was also conducted for 25 cycles.

The abrasion tests were also conducted in fabric form using a Martindale abrasion tester (902 Mini Martindale, James Heal Ltd, Halifax, UK) for 6000 abrasion cycles (12000 rubs) according to BS EN ISO 12947-2:201645. Microscopic images were taken before tests and after every 1000 cycles, with the test sample remaining fixed to the abrasion tester. For wash durability and abrasion tests fabrics were woven using solar-E-yarns embedded with a single SC.

3 RESULTS AND DISCUSSION

3.1 Solar-E-yarns characterization

The performance of the solar-E-yarns at different stages in the fabrication process was evaluated (Fig. 5).

Figure 4 – The experimental setup for conducting measurements for solar-E-yarns and solar cell embedded fabrics used with closed loop temperature control system.

2.4 Durability testing

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Figure 5 – Average of the (a) short circuit current (Isc), (b) open-circuit voltage (VOC) and (c) maximum power output of the twenty solar-E-yarns at different stages of the yarn fabrication process. Error bars represent the standard deviation.

The solar-micro-pod filament showed an ~ 12% increase in Isc and Pmax, possibly due to the light concentrating effect of the cylindrical RMP and reduction in Fresnel reflection after encapsulation. After covering the RMP
with the fibrous sheath a ~35% reduction in $I_{SC}$ and ~42% reduction in $P_{MAX}$ (compared to the SC only values) was observed due to the reduction in light flux. This was due to the shading of the SC by the fibrous sheath.

The shading effect by the fibrous sheath could mainly be attributed to the scattering of light by individual textile fibres at the fibre-air interfaces, as explained by the Fresnel equation. According to the Fresnel equation the amount of light reflected at a fibre-air interface is mainly dependent on the difference in refractive indices ($\Delta n$) of the two materials on either sides of the interface ($n_{air} =1$, $n_{textile}=1.51$). Based on this theory, the shading effect by the fibrous sheath could be minimized by replacing the air spaces between the fibres with a material that had a refractive index similar to the textile fibres. This was proven by impregnating the fibrous sheath of solar-E-yarns with the same encapsulation resin used for the RMP that has a refractive index of 1.55, as shown in Table I.

Table I: Effect on resin impregnation on short-circuit current ($I_{SC}$) of solar-E-yarns. Results were normalized to solar cell only values.

<table>
<thead>
<tr>
<th>Resin Impregnation</th>
<th>$\Delta n$</th>
<th>Normalized $I_{SC}$ (%)</th>
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</thead>
<tbody>
<tr>
<td>No</td>
<td>0.51</td>
<td>66%</td>
</tr>
<tr>
<td>Yes</td>
<td>0.04</td>
<td>119%</td>
</tr>
</tbody>
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This modification however, significantly affected the hand-feel of the solar-E-yarn, hence this was not employed when preparing solar energy harvesting fabrics.

3.2 Solar energy harvesting fabric characterisation

The solar energy harvesting fabric had a 44.5 mm × 45.5 mm active area. The fabric (Fig. 6) was soft, conformable to three-dimensional shapes and possessed the same aesthetics of a normal textile. The porous structure of the sheath and discrete RMPs readily allowed air and moisture to transfer through the E-yarn structure.

Figure 6 - The solar energy harvesting fabric created by weaving twenty solar-E-yarns together.

The demonstrator fabric was tested under 100% and 50% of one sun illumination (1000 W/m², AM 1.5 global spectra), with the results shown in Fig. 7. The fabric generated 45.5 mW of power and a fill factor of 0.59 with a power density of ~2.15 mW/cm² at 100% one sun intensity. The power generated by the fabric was ~8% lower than the sum of the power generated by the twenty solar-E-yarns individually. This could be due to the mismatch in losses induced by variations in solar-E-yarn alignment within the fabric. When the measurements of the solar energy harvesting fabric at 100% and 50% one sun intensities were compared, it was clear that $I_{SC}$ had a linear relationship and $V_{OC}$ exhibited a logarithmic relationship with light intensity. This was consistent with the theory on behaviour for SCs at varying light intensities.

The SC embedded fabric was also capable of charging a mobile phone with a 1000mAh battery, and a fitness tracker with a 50mAh battery. Based on the experimental results, it was estimated that to generate a sufficient amount of power to charge more powerful mobile device, such as a smart phone, the photoactive area would need to be increased.

3.4 Durability tests

All of the hand washed yarns functioned correctly (i.e. the performance was similar to before washing) after 25 hand wash cycles or 15 machine wash cycles. The change in $I_{SC}$ and $V_{OC}$ for solar-E-yarns after every five washes are shown in Fig. 8. The $P_{MAX}$ values showed a ~13.5% and a ~10.4% reduction after 25 machine wash cycles and 25 hand wash cycles, which was due to the compound effect of changes in $I_{SC}$, $V_{OC}$ and FF.
4 CONCLUSION

A novel approach for creating a solar energy harvesting textile for powering wearable and mobile devices has been successfully demonstrated in this work. The solar-E-yarns and resultant energy harvesting fabric managed to generate sufficient levels of power while retaining desirable textile properties such as softness, drapability and breathability. The solar cell embedded fabrics were durable under machine washing and did not show significant deterioration in performance after being subjected to abrasion testing. This novel method of creating energy harvesting textiles has the potential to disrupt the present-day methods of powering wearable and mobile electronic devices in the future, where the consumer will not have to compromise on reusability, appearance or comfort.

5 REFERENCES