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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 2.15mW/cm^2 under one sun (1000 W/m^2) 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 energy[3] and maturity of photovoltaic (PV) technologies[4]. A number of fabrication techniques such as printing[5], coating[6] or laminating[7] organic photovoltaics (OPVs) [8] and thin film PVs[9] 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 wires[10] or flexible PV tapes[8] 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 conditions[11,12], 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) (Fig .1) technology[13-17] 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/cm^2 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.

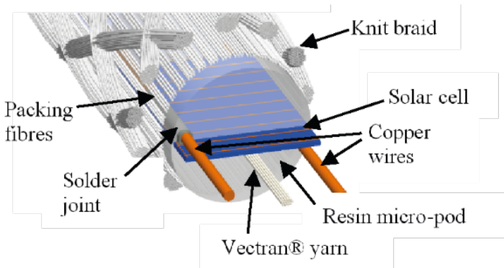

Figure 1 - Cross sectional illustration of a solar-E-yarn.

2 MATERIALS AND METHODS

2.1 Fabricating of solar-E-yarns

Solar-E-yarn preparation involved three steps: First, ten 1.5 mm x 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 SC 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 knit-braiding 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)).

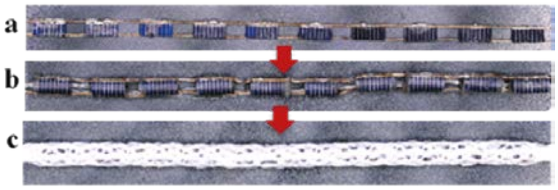

Figure 2 - Fabrication of solar-E-yarns (**a**) Ten miniature solar cells soldered onto two fine copper wires. (**b**) The soldered solar cells individually encapsulated within resin micro-pods. (**c**) The final solar-E-yarn after covering the solar-micro-pod filament with textile fibres.

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.

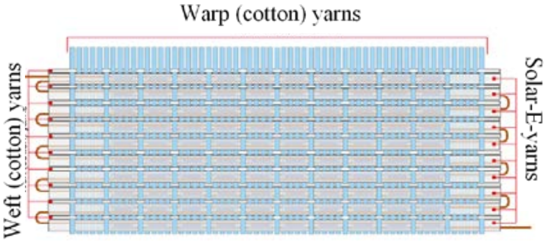

Figure 3 - Woven structure and electrical network of one mini-module of the solar cell embedded yarn demonstrator.

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/m^2) 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 100M Ω 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).

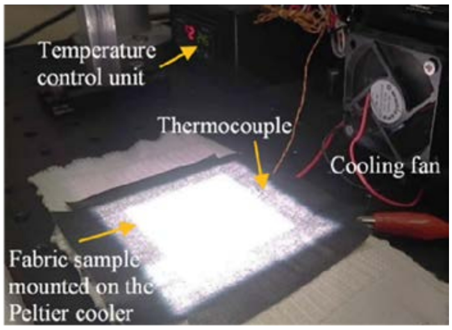

Figure 4 – The experimental setup for conducting measuremnts for solar-E-yarns and solar cell embedded fabrics used a with closed loop temperature control system.

2.4 Durability testing

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 (AATCC 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 remainnig 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).

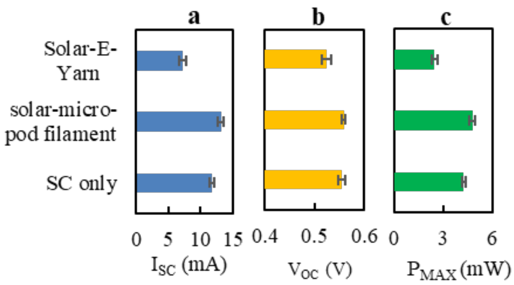

Figure 5 - Average of the (**a**) short circuit current (I_{SC}), (**b**) open-circuit voltage (V_{OC}) and (**c**) maximum power output of the twenty solar-E-yarns at different stages of the yarn fabrication process. Error bars represent the standard deviation.

The solar-micro-pod filament showed an ~ 12% increase in I_{SC} and P_{MAX}, possibly due to the light concetrating 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[18]. According to the Fresnel equation the amount of light reflected at a fibre-air interface is mainly dependent on the difference in refractive indeces (Δn) of the two materials on either sides of the interface (n_{air} =1, n_{fibre}=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 onlv values.

Resin Impregnation	*Δn*	*Normalized I_{SC} (%)*
No	0.51	66%
Yes	0.04	119%

This modification however, significantly affected the hand-feel of the solar-E-yarn, hence this was not employed when prepearing 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.

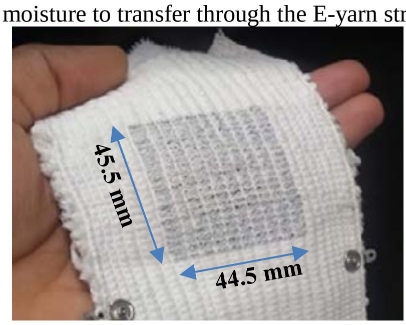

Figure 6 - The solar energy harvesting fabric created by weaving twenty solar-E-yarns together.

The demonstrator fabric was tested under 100% and 50% of one sun illumination (1000 W/m^2, AM 1.5 global spectra), withthe 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/cm^2 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 intensity were compared, it was clear that I_{SC} had a liner relationship and V_{OC} exhibited a logarithmic relationship with light intensity. This was consistent with the theory on beahaviour for SCs at varying light intensities[19].

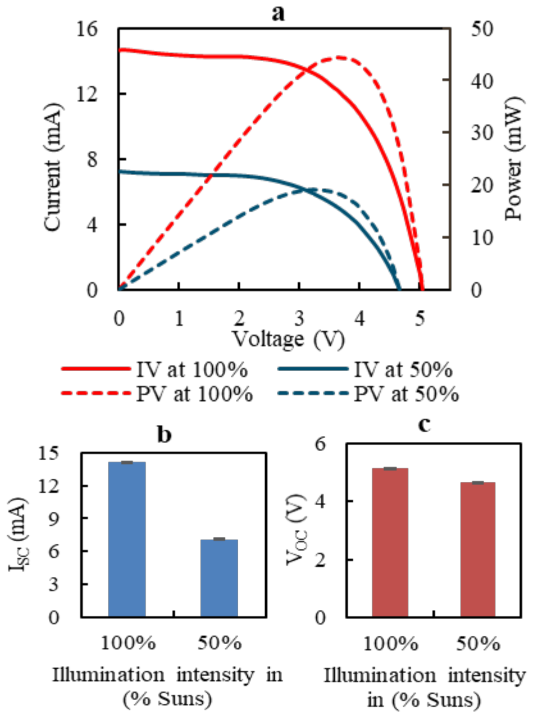

Figure 7 - (**a**) The current-voltage (IV) and power voltage (PV) characteristics (**b**) short-circuit-current and (**c**) open-circuit voltage of the solar cell embedded fabric demonstrator under 100% and 50% of one sun illumination. Error bars show SD of five repeat readings.

3.3 Solar enrgy harvesting capability demonstrations

The solar fabric demonstrator was capable of charging of different energy storage devices under one sun illumination as shown in the Table II below.

Table II - Voltage and charging times for three different electrical energy storage devices, charged using the solar cell embedded fabric demonstrator.

Storage device	*Charged voltage*	*Charging time*
47 mF (5.5 V) supercapacitor	0.0 - 4.9 V	15 s
15 mAh (3.7 V) Li-ion battery	2.0 – 3.7 V	10 min
380 mAh (3.7 V) Li-polymer battery	3.10 – 3.55 V	60 min

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 wahes 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.

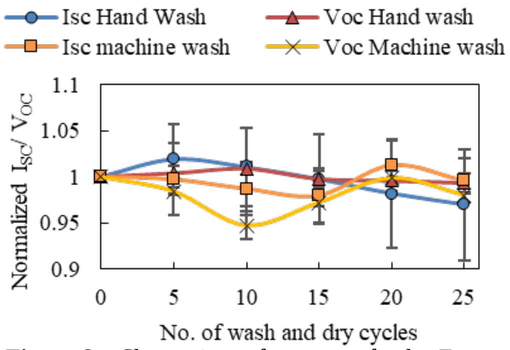

Figure 8 - Change in performance of solar-E-yarns in fabric form after hand washing and machine washing. Error bars show SD of measuremnts of functioning yarns.

The excellent wash durability of the fabric embedded solar-E-yarns can be attributed to the protection provided by the RMP to individual SCs and conformability of the solar-E-yarns under external mechanical strains without undergoing failure or fractures.

When the I_{SC} and V_{OC} values for solar-E-yarns woven into fabrics were compared before and after 6000 abrasion cycles, no significant change in performance was observed. However, a slight change in the surface appearance of the solar-E-yarns were observed after abrasion cycles, due to insignificant levels of fibre breakage and fibre redistribution as observed in Fig. 9.

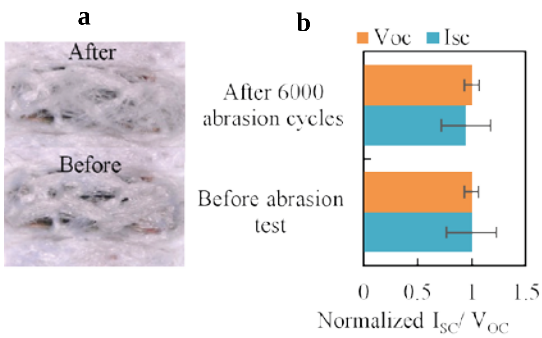

Figure 9 - Change in (**a**) appearance and (**b**) performance of solar-E-yarns in fabric form after 6000 abrasion cycles.

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.

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