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Energy harvesting "3-D knitted spacer" based piezoelectric textiles

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Abstract. The piezoelectric effect in Poly(vinylidene fluoride), PVDF, was discovered over four decades ago and since then, significant work has been carried out aiming at the production of high β-phase fibres and their integration into fabric structures for energy harvesting. However, little work has been done in the area of production of "true piezoelectric fabric structures" based on flexible polymeric materials such as PVDF. In this work, we demonstrate "3-D knitted spacer" technology based all-fibre piezoelectric fabrics as power generators and energy harvesters. The knitted single-structure piezoelectric generator consists of high β-phase (~80%) piezoelectric PVDF monofilaments as the spacer yarn interconnected between silver (Ag) coated polyamide multifilament yarn layers acting as the top and bottom electrodes. The novel and unique textile structure provides an output power density in the range of 1.10-5.10 μWcm^{-2} at applied impact pressures in the range of 0.02-0.10 MPa, thus providing significantly higher power outputs and efficiencies over the existing 2-D woven and nonwoven piezoelectric structures. The high energy efficiency, mechanical durability and comfort of the soft, flexible and all-fibre based power generator is highly attractive for a variety of potential applications such as wearable electronic systems and energy harvesters charged from ambient environment or by human movement.

Keywords: Poly(vinylidene fluoride) PVDF, β phase, energy harvesting, piezoelectric effect

1. Introduction

The harvesting of waste energy from ambient environment and human movement has long been considered as an attractive alternative over traditional rechargeable batteries for providing electrical power to low-energy consumption devices such as wireless body worn sensors and wearable consumer electronics [1-3]. Recently, inorganic nanowires of ZnO, InN, GaN, CdS, ZnS and PZT have shown remarkable ability to harvest energy from small mechanical movements and have shown higher energy conversion efficiency as compared to their micro and macro sized counterparts which was attributed to size-effects, decreased defects and improved mechanical flexibility [1-3]. However, it should be noted that these materials are quite brittle in nature, work only at small levels of strain (< 1 %) and are much harder to integrate on a large scale and quite expensive to produce [1-3]. Moreover, for wearable applications, the energy harvesting devices should provide the right "feel" and comfort as well to the wearer. The current problems associated with flexible piezoelectric generators are; (i) low throughput and long and tedious processing techniques; (ii) low output power densities; and (iii) lack of integration techniques [1-3]. Moreover, for achieving truly integrated piezoelectric materials in textile structures, the durability and the "feel" of the piezoelectric structures needs to be tailored. For energy harvesting from human movement, the fibre based electrical power generators are highly desirable as they are light weight and comfortable and look no different from the conventional fabrics. The conjunction of piezoelectric materials in fibres and therefore fabrics offers a simple route for the building of soft piezoelectric generators. The flexible textile structures can themselves be designed so as to provide piezoelectric output on low levels of strains and loadings while providing high fatigue resistance under a large number of variable mechanical deformation and loading cycles. To address this, we have developed three-dimensional piezoelectric fabrics based on "3-D knitted spacer" textile technology [4].

2. Experimental

2.1. Continuous melt-spinning extrusion of poled PVDF monofilaments

Melt spinning of PVDF homopolymer SOLEF 1008, supplied by Solvay Solexis Ltd., was used for the processing of PVDF fibres on a bi-component pilot plant extruder. The polymer pellets are transported across the length of the heated barrel (temp. profile: 190, 200, 210, 220 °C, across the four heated barrel zones) via a screw, where the melt exits the monofilament spinneret (Φ = 0.8 mm, 230 °C) at a pressure of approx. 100-105 bar where the filament is cooled down by using an air quench operating at 20 °C. At this point, the melt is taken up by a draw down godet rotating at 101 mpm (metres per minute). The filament is then passed upon two pairs of heated godets, rotating at 102 and 505 mpm, respectively, producing the change in the orientation of the chains and the crystalline structure of the filament. The draw ratio of 5:1 was found to be the optimal value of the drawing where a high β phase (~ 80 %) was observed and the filament could be processed continuously. While the filaments are being drawn between 2nd and 3rd pair of godets, an electric field of 0.6 MV/m is applied across the filament between two electrodes to further enhance the β phase of the filaments [4-7].

2.2. Knitting of 3-D spacer piezoelectric fabrics

The fabrics were knitted on an E20 circular weft knitting double-jersey spacer machine with a 30" dia., at a machine speed of 30 rpm (at Baltex Speciality Knitters Ltd U.K.). Figure 1(a, b) illustrates the specific knitted structure produced in this work by using three different yarns; (i) conductive yarn A; (ii) insulating yarn B; and (iii) piezoelectric yarn C. The conductive yarn A (Shieldex® Ag coated PA66, 143/34 dtex, resistivity of <1kΩ/m, supplied by Statex GmbH), is plated on the outside of each of the fabric face; the insulating yarn B (84 dtex, false-twist texturized polyester yarn) is plated inside the structure in such a manner that it shows on the inside of the two fabric faces and finally the piezoelectric monofilament spacer yarn C (300 dtex), is tucked inside the two fabric faces [4, 5]. It should be noted that yarn C is tucked on both cylinder and dial needles in such a manner that it does not protrude through either of the fabric faces and always remains inside the two faces keeping them apart. The total thickness of the fabric structures developed in this work was approximately 3.5mm; however, it should be noted that this thickness can be varied between 2mm and 60 mm, depending on the type of knitting machine (warp or weft knitting) used and the end-use application.

3. Results and discussion

For the all fibre piezoelectric generator produced in this work, with an effective area of 15 cm x 5.3 cm, the peak values of the open-circuit voltage and current were found to be 14 V and 29.8 μA, respectively at an applied pressure of 0.106 MPa. In fact, the total power output increases from 0.08 mW to 0.4 mW over the measured impact range of 0.02 MPa to 0.106 MPa, as shown in Figure 2(a) to (c).

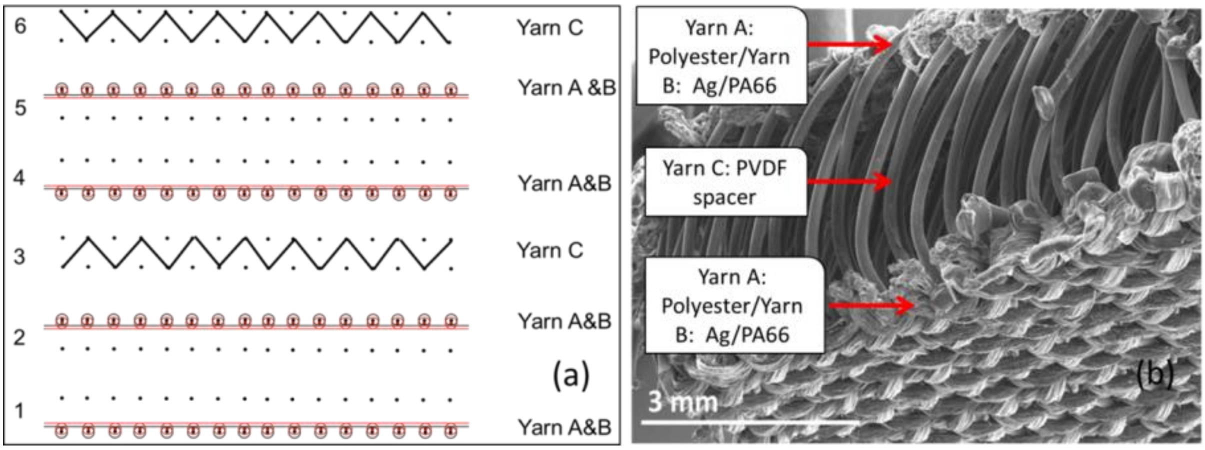

Figure 1. (a) Schematic of the fabric structure with the position of various yarns in the structure and (b) cross-sectional SEM image of the actual fabric clearly showing the position of piezoelectric and conductive yarns [4].

The power output of the piezoelectric fabric can be modelled by using the following equation:

$$Power\ output\ (\mu\text{Wcm}^{-2}) = 4.98 - \frac{5.10}{\{1 + exp\ (x - 0.03/0.008)\}}$$

where x is the applied impact pressure and power output is measured in μWcm^{-2}. The 3-D structures provide nearly five times the output power density, with a maximum power density, with a maximum power density of 5.07 μWcm^{-2}, verses 1.18 μWcm^{-2} for knitted 2-D structures, as shown in Figure 2(d).

The power densities obtained from these 3-D piezofabrics are much higher than those reported for 2-D nonwoven $NaNbO_3$–PVDF nanofibre based generators which provide a power output of 2.15 μWcm^{-2}, and electrospun nonwoven PVDF fabrics which generated nearly 3.2 μWcm^{-2} [8]. These values are also significantly higher than those achieved by PVDF nanofibre based generators and $NaNbO_3$ nanowires, which provide an effective power output of 0.115μWcm^{-2} [9]. The excellent performance of our novel generator can be attributed to the following factors; (i) high β phase of the PVDF fibres; (ii) enhanced charge collection due to intimate contact between the PVDF fibres and conductive yarns, leading to improved efficiency; and (iii) transfer of the uniform compression pressure across the fabric surface.

The technologies of knitting of 3-D spacer fabrics have been around for over three decades now and the underlying technology and understanding are highly developed. However, we understand that there have been no previous reports on the use of 3-D spacers fabrics as energy harvesting fabrics and as is the case with every technological development , there are some foreseeable technical challenges which include; (i) optimisation of positioning, spacing and thickness of the spacer piezoelectric yarn and its arrangement in the 3-D structure to enhance the piezoelectric response; (ii) optimization of fabric density and thickness of the spacer fabric for different applications; (iii) ensuring that the conducting yarns used in the opposite faces do not come in contact with each other during the knitting process, or during the cutting procedure ; (iv) as the textiles are intended for use as wearable energy harvesting textiles, the important factors, include air permeability, wicking properties, stretchability and recovery need to be tested and controlled to provide a high level of comfort to the user; and finally (v) the effects of washing, regular use for long periods of time and durability and integrity of the fabric need to be verified to ensure reproducibility of the piezoelectric response and provide a certain lifetime value for the fabric.

Further work on the coupled mechanical and piezoelectric analysis of the 3-D knitted fabric generators is under way to ascertain the complex relationship between the structure of the fabric and power output and to enhance it further.

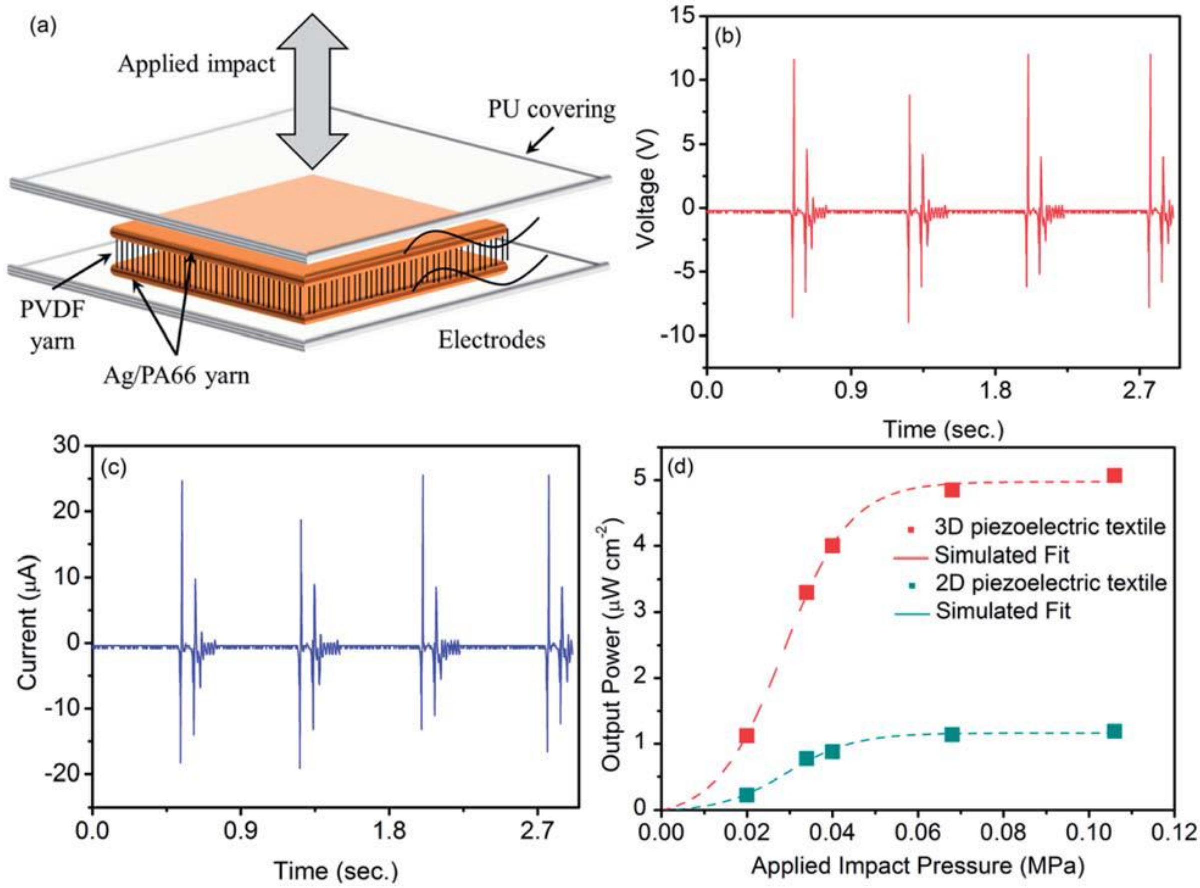

Figure 2. (a) Schematic structure of the packaged 3-D piezoelectric fabric power generator; typical (b) voltage and (c) current outputs of the 3-D piezoelectric fabric (obtained at an impact pressure of 0.034 MPa across a 470 kΩ load); and (d) variation of total output power as a function of applied impact pressure for 2-D and 3-D piezoelectric fabrics [4].

4. Conclusions

A novel knitted all fibre piezoelectric nanogenerator comprising of principally β-phase PVDF fibres in a “3-D knitted spacer” structure, with Ag/PA66 yarn as the charge collecting conducting faces, has been designed, developed and fully characterised. The phase change from a predominately α–phase in raw pallets to a nearly 80% β-phase in filaments has been obtained by drawing of the filaments under an applied electric field. The α to β phase transition has been quantified by using a variety of techniques including FTIR, DSC, NMR, XRD and PFM.

The 3-D knitted spacer piezoelectric fabrics exhibit power density in the range of 1.10μWcm^{-2} to 5.10 μWcm^{-2} at applied impact pressures of 0.02 MPa to 0.10 MPa. This all fibre piezoelectric fabric possesses the advantage of efficient charge collection due to intimate contact of electrodes and uniform distribution of pressure on the fabric surface, leading to enhanced performance. Moreover, the “feel” of the all-fibre piezoelectric generator is not very different from any other conventional textile material and is soft and flexible providing potential maximum level of comfort to the wearer. Bearing all these merits in mind, we believe that our method of producing large quantities of high quality piezoelectric yarn and piezoelectric fabric provides an effective option for the development of high

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performance energy-harvesting textile structures for electronic devices that could be charged from ambient environment or by human movement.

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