Textile based ferroelectret for wearable energy harvesting

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Abstract. Ferroelectrets are typically thin polymer foams that convert mechanical energy into electrical energy. This paper reports the fabrication and testing of a textile based ferroelectret made from two fluorinated ethylene propylene (FEP) films and a conventional textile (cotton, poly-cotton and silk) formed into a sandwich structure. These layers are laminated together and achieve a maximum measured stabilized piezoelectric coefficient $d_{33}$ of 987 pC/N for the FEP-silk ferroelectret, which is 85\% of its initial piezoelectric coefficients $d_{33}$ after polarization.

1. Introduction

With the development in the field of wearable electronics, there is a demand for renewable energy supplies suitable for long life applications [1-2]. Kinetic energy harvesting technologies that gather energy from human activities, such as running and walking, has received growing attention over the last decade. In the past, research interests have been focused on the conventional piezoelectric materials such as lead zirconate titanate (PZT) and polyvinylidene fluoride (PVDF). However, both of them are not ideal for wearable energy harvesting applications. PZT is physically hard and brittle and PVDF has low piezoelectric properties [3]. Therefore, there is the need to develop a piezoelectric material with high piezoelectric activity, low Young’s modulus and the ability to stretch and conform for wearable applications. Functionalising a standard textile such that it becomes able to harvest mechanical energy would meet this requirement and be extremely useful for e-textile applications.

Ferroelectrets are typically thin films of polymer foam which have electric charge stored on the surfaces of its internal voids, exhibiting strong piezoelectric properties after charging [4]. The typical internal structure of a ferroelectret foam is randomly arranged cellular voids with positive and negative charges stored separately on each surface of the void. Due to the material properties of the polymer and its internal structure, the elastic modulus of the ferroelectret is low. The ferroelectret is readily compressible and will undergo large deformation when under a compressive force, which results in a strong piezoelectric effect. Due to its increased piezoelectric properties in comparison with other piezoelectric materials, numerous applications have been proposed, such as acoustic transducers, high frequency loudspeakers, ultrasonic transmitters and receivers, hydrophones and accelerometers [5]. The soft, flexible nature of the polymer ferroelectret makes it highly suitable for use in wearable applications. We have previously presented a low cost and straightforward fabrication process for realising a stable ferroelectret material based upon sandwiching a thin piece of standard foam between two fluorinated ethylene propylene (FEP) films. In this work we report a textile based version of the ferroelectret in which the foam insert is replaced by a single standard fabric layer using a combination...
of processes commonly employed by the textile industry such as screen printing, lamination and spray coating [6].

2. Device description
The mechanics of a ferroelectret materials piezoelectric like behaviour is due to a macroscopic dipole moment that arises due to changes in the geometry of the voids. After electric charging, positive and negative charges are trapped at the internal gas polymer interfaces on either side of the void. The amount of trapped charge and the distance between the charged surfaces determine the magnitude of the macroscopic moment. When the ferroelectret is compressed, to maintain electrical neutrality, the electrical field in the void is compensated by induced charge on the outer electrodes that is generated by the trapped internal charge. The charge generation at the electrode surface is identical to the piezoelectric effect and can be characterised using piezoelectric coefficients such as \(d_{33}\) that relates the charge generated to the applied compressive force. The magnitude of the \(d_{33}\) of the ferroelectret is determined by its material proprieties, i.e. the materials ability to trap charge, its void geometry and Young’ modulus. The low Young’s modulus of the foam ferroelectret allows large deformation of the electrically charged voids when compressed resulting in large measured \(d_{33}\) values. This mechanism has been previously characterised and theoretically analysed [7-14].

The textile based ferroelectret has a sandwich structure that consists two thin fluorinated ethylene propylene (FEP) films separated by a thin textile layer, as shown in Figure 1 (a). A thin layer aluminium (Al) metal electrode is evaporated on to one surface of the FEP films. The two FEP films are adhesively bonded to the opposite surfaces of a standard textile that provides a soft mechanical separating layer electrically isolating the FEP films. Ethylene-vinyl acetate (EVA) polymer must be first soaked into textile at the location of the adhesive bond to form a stable seal around the active area of the ferroelectret. This is required to prevent charge leaking from the surface of the FEP. The Young’s modulus of the FEP-textile ferroelectret is determined by the Young’s modulus of the FEP/textile assembly. An image of fabricated FEP-cotton textile ferroelectret is shown in Figure 1 (b).

![Figure 1. (a) The schematic drawing of FEP-textile ferroelectret (b) The image of a FEP-cotton textile ferroelectret](image-url)
3. Experimental detail

3.1. Fabrication

The schematic of FEP-textile ferroelectret fabrication process is illustrated in Figure 2. The FEP sheets were purchased from DuPont. The sheet size obtained was 304 mm × 200 mm, with a thickness of 25 µm and these were cut into samples of size of 80 mm × 80 mm. A 100 nm thick aluminium film was evaporated on to one side of the FEP films (Bak600 Evaporator, Leybold Ltd.). Adhesive tape was used as a lift of layer to define a 60 mm × 60 mm electrode area. Three different types of textile (cotton, silk and poly-cotton) were cut into sample sizes of 120 mm × 120 mm. Ethylene-vinyl acetate (EVA) binder (0.5 g) was dissolved 1,2,4-Trichlorobenzene solvent (10 mL) and was spray coated from both sides of the textile through a shadow mask. This was left at room temperature in air to cure forming an annulus shaped seal around the active area. A thin (30 µm) layer of double sided adhesive tape (Tesa® 4983) was used to bond the uncoated side of the FEP film to the textile cotton at the location of the EVA seal. To charge the ferroelectret sandwich structure, the assembly was subject to a high electric field in a corona. A corona-tip voltage of -25 kV and a charging time of 60 seconds was employed.

![Figure 2. The Schematic of fabrication processes](image)

3.2. Sample characterization

To investigate how the properties of the FEP-textile ferroelectret are affected by the different textiles, the $d_{33}$ coefficient of the samples were measured using a PieziMeter (PM300, Piezotest Ltd). The $d_{33}$ coefficient was measured over a 1-month period with the samples being stored at room temperature under normal atmospheric conditions. In order to evaluate the energy harvesting ability of the FEP-textile under compressive load, samples were placed in an Instron dynamic load testing instrument (ElectroPuls E1000, Instron Ltd). The test samples were subjected to a 350 N force at a frequency of 1 Hz with a square wave drive signal and the voltage output was observed on a digital oscilloscope. The ElectroPuls E1000 was also used to measure the tensile elastic modulus.
4. Results and discussions

Table 1 lists the generated peak output voltage, measured piezoelectric coefficient $d_{33}$ and Young’s modulus for the three textiles and the assembled FEP-textile ferroelectrets. In the previous paper with the foam inserts, it was found that for a fixed foam thickness the lower the Young’s modulus of the foam, the higher the piezoelectric coefficient [6]. However, in this case the textile thickness is different in each case and this should also be considered. This is because the textile thickness has an increasing influence on the ferroelectret internal electric field as the thickness reduces. The thinner ferroelectret assembly can achieve a higher surface charge density than for the thicker textile ferroelectrets for the same charging voltage, resulting in higher piezoelectric-like properties. This is demonstrated by the previously presented models that predict the piezoelectricity of ferroelectrets [6] that have been used to calculate the $d_{33}$ and explore how it varies with the thickness of the three textiles as shown in Figure 3. The theoretical and experimental data together show that the silk ferroelectret has the largest $d_{33}$ despite having the highest Young’s modulus, and this is due to the fact it is the thinnest of the three fabrics. From table 1, the maximal peak output voltage of 21 V and piezoelectric coefficient $d_{33}$ 970 pC/N are achieved by the FEP-silk ferroelectret. In addition, the long-term stability of the three different FEP-textile ferroelectret is shown in Figure 4. From this figure, it can be observed that all three FEP-textile ferroelectret demonstrate an initial decay in the $d_{33}$ coefficients up to around 20 days after which it remains constant. The FEP-silk ferroelectret retained around 85% of its initial piezoelectric coefficients $d_{33}$ over 30 days. The other two types of textile ferroelectret retained around 92% of their initial piezoelectric coefficient $d_{33}$ over 30 days.

| Thickness (µm) | Young’s modulus (MPa) | Fabricated Ferroelectret Young’s modulus (MPa) | Measured piezoelectric coefficient $d_{33}$ (pC/N) | Measured Peak output voltage (V) |
|----------------|------------------------|-----------------------------------------------|-----------------------------------------------|---------------------------------|
| Cotton         | 500                    | 83                                            | 99                                            | 485                            | 13                              |
| Poly-cotton    | 300                    | 104                                           | 334                                           | 382                            | 10                              |
| Silk           | 50                     | 452                                           | 467                                           | 987                            | 21                              |

Table 1. The material parameters, peak voltage and measured piezoelectric coefficient $d_{33}$ for the three different FEP-textiles ferroelectret

Figure 3. The predicated piezoelectric coefficient $d_{33}$ as a function of textile thickness for the three fabrics

Figure 4. Piezoelectric coefficient $d_{33}$ decay over 30 days
5. Conclusions
In this work, a fabrication method and testing for a textile-based ferroelectret has been reported. Three different types of textile (cotton, poly-cotton, and silk) based ferroelectret have been fabricated. The piezoelectric properties of the fabricated FEP-textile are improved by utilizing a thinner textile. The reason of it is the thinner ferroelectret can achieve a higher surface charge density based on the same charging voltage resulting in higher piezoelectric-like properties. The quasi-piezoelectric properties are also affected by the Young’s modulus of the fabric with lower stiffness textiles resulting in higher $d_{33}$ coefficients. The best solution would be to use a thin, soft textile with a low Young’s modulus. This work has shown it is relatively straightforward to functionalise any normal textile and convert it into a ferroelectret material that could be used for energy harvesting or sensing applications.

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