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An easy to assemble ferroelectret for human body energy harvesting

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Abstract

Ferroelectret is a thin and flexible cellular polymer foam that generates electrical power under mechanical force. This paper reports the fabrication and testing of an easy to assemble ferroelectret which is made from two fluorinated ethylene propylene (FEP) films and a standard polymer foam formed into a sandwich structure. The measured piezoelectric coefficient d_{33} of the FEP-porous polymer ferroelectret is 1000 pC/N. The energy harvester based on the FEP-porous polymer ferroelectret generate an output power of 6.4 µW. This is corresponding to volume unit power output of 62.4 µW/cm^3. The practical electromechanical coupling factor is achieved at 0.107. Within 40 seconds, a 10 µF capacitor is charged up to 0.2 V by the FEP-porous polymer ferroelectret harvester through a rectifier.

Keywords

FEP, ferroelectret, human body energy harvesting

1. Introduction

With the development of wearable technology, there is a significant trend for multi-functionality, intelligence and miniaturization [1-2]. One aspect of wearable technologies is the challenge of supplying power, and this makes low power operation essential. There is also the motivation to investigate alternative power supplies such as energy harvesting to augment the typical battery and extend time between charges [3]. Energy harvesting technologies that, for example, harvests energy from human movement can potentially provide a power source for these wearable devices. Harvesting energy from human motion is challenging due to the large amplitude low frequency movements [3] and whilst piezoelectric materials are widely used, conventional piezoelectric materials such as bulk ceramic lead zirconate titanate (PZT) is hard and brittle and is therefore unsuitable for most applications. Other forms of PZT have been used successfully in some applications such as capturing energy from footfalls to power a shoe mounted sensor system and harvesting energy from heart motion to supply a pacemaker [4-5]. The piezoelectric polymer polyvinylidene fluoride (PVDF) has also been used and this has the advantage of being soft and flexible but has low piezoelectric properties [6]. 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.

Ferroelectrets, also known as piezoelectrets, are thin flexible polymer films that store electric charges in internal voids. These exhibit strong piezoelectric effects and are typically flexible compliant materials highly compatible with wearable applications [7]. 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, such as polypropylene (PP) ferroelectret [8]. Due to the low elastic modulus of the polymer, the electrically charged voids will undergo large deformation when compressed, leading to strong piezoelectric effect. Due to its improved piezoelectric properties in comparison with other material, numerous applications of have been suggested, such as acoustic transducers (high frequency loudspeakers, ultrasonic transmitters and receivers and hydrophones) and accelerometers [9].

Most of the existing commercial ferroelectret foams are produced using a blow and extrusion process on polymer films. The individual void geometry and overall cellular structure of the ferroelectret foam are typically ill-controlled due to the stochastic nature of these fabrication processes. This traditional fabrication process is expensive, complex is not suitable for fabricating ferroelectrets from other polymer materials [10].

In this work, a low cost and straightforward fabrication method for combining a fluorinated ethylene propylene (FEP) film with standard polymer foam to realise a ferroelectret transducer is presented. The flexible polymer foam is sandwiched between two thin FEP films and forms a mechanical spacer. FEP is an excellent electret material that can store a high level of charge and is stable over time. The foam acts as a spring that generates a mechanical restoring force returning the electret to its original geometry after the applied force is removed. This paper introduces the ferroelectret design, a theoretical model for predicting performance and the fabrication method. The ferroelectret is characterised experimentally to determine the piezoelectric coefficient d_{33}, the stability of the device over time and the materials energy harvesting potential by charging a capacitor.

2. Device description

The device has a sandwich structure that consists two thin FEP films separated by a porous polymer foam, as shown in Figure 1 (a). The 2 cm × 2cm square-shaped electrodes are made of aluminium metal foil which is bonded to the FEP films. The two FEP films are connected mechanically, and electrically isolated from each other, by double-sided adhesive tape along the porous polymer edges. A non-conductive polymer foam spacer is inserted between the two FEP films. The photograph of the device is shown in Figure 1 (b).

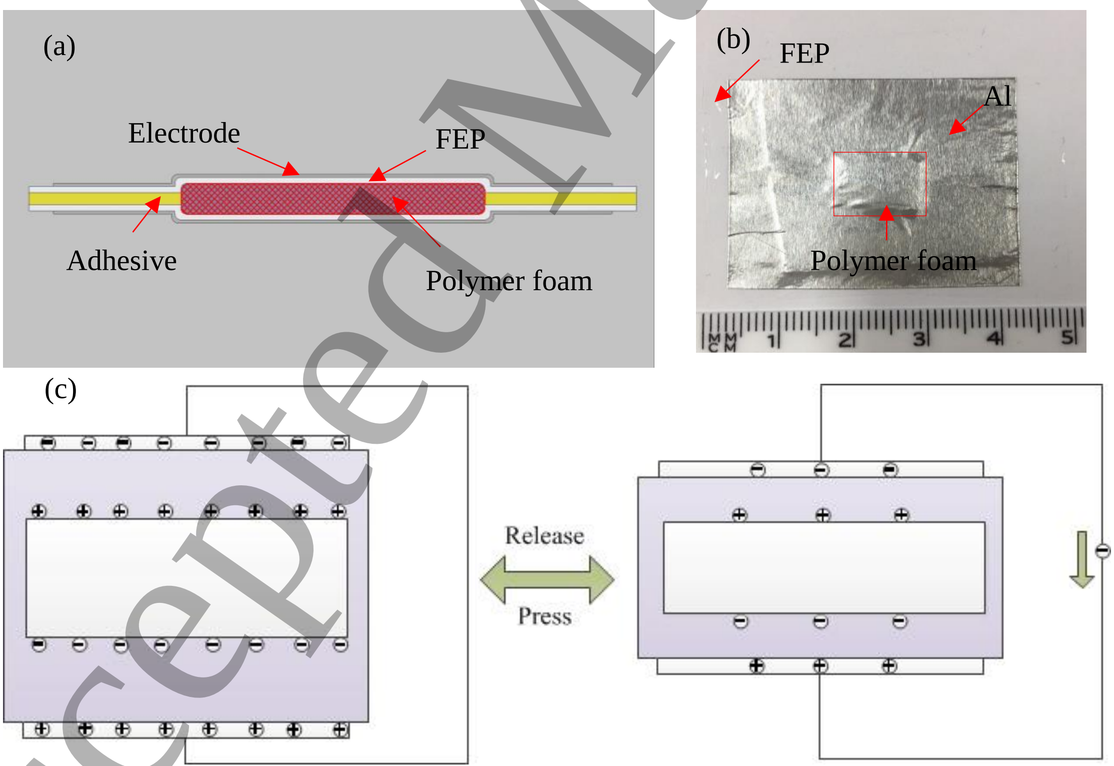

Figure 1. Schematic (a), photograph (b), and working principle (c) of the proposed FEP-porous polymer ferroelectret

The device is operated in the d_{33} mode as shown in figure 1 (c). During polarisation, the positive and negative charges are trapped on the upper and lower FEP-polymer foam interface.

A macroscopic dipole moment is formed by the separated charges resulting in piezoelectric like properties. The macroscopic dipole moment is determined by two factors: the amount of charge and distance between the separated charges. When the ferroelectret is compressed, to maintain the electrical neutrality, the electrical field in the void is compensated by induced charge on the electrodes that are generated by the stored internal charge. The low elastic modulus of the polymer foam allows large deformation of electrically charged void when the device is compressed by a mechanical stress. The magnitude of the piezoelectric property d_{33} of the ferroelectret is determined by the amount of stored charge and the Young's modulus of the ferroelectret. If the electrodes are connected to a load, a current is generated. In addition to being highly compressible and flexible, the foam also prevents the FEP films from touching which would otherwise discharge the trapped charge rendering the ferroelectret inactive.

The piezoelectric like properties of ferroelectrets has already been theoretically analysed [11-18]. In order to analyse the piezoelectricity properties of the proposed ferroelectret, a simplified model for the piezoelectricity of the FEP-porous polymer ferroelectret is illustrated in Figure 2.

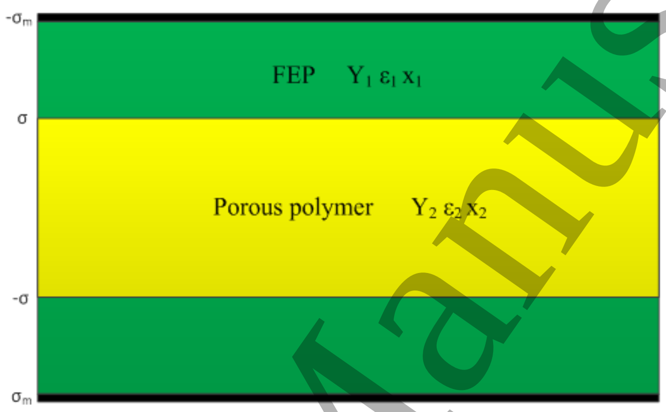

Figure 2. The layer model for the FEP polymer foam ferroelectret.

For this simplified model, the electric field in the FEP layers (E_1) and porous layer (E_2) can be obtained from Gauss' law for the interfaces:

$$E_1 = \frac{\sigma_m}{\varepsilon_1} \text{ and } E_2 = \frac{\sigma_m - \sigma}{\varepsilon_2} \tag{1}$$

Where σ_m is the charge density on the electrodes; σ is the charge density on void surface; and ε_1 and ε_2 are the dielectric constant of FEP and polymer foam, respectively.

From Kirchhoff's second law under short circuit conditions:

$$V = \int E\, dx = 2x_1E_1 + x_2E_2 = 0 \tag{2}$$

Where V is the electric potential across the electrode pair and x_1 and x_2 are the thickness of FEP and porous polymer layers respectively. Substituting Eq. (2) into Eq. (1) leads to:

$$\sigma_m = \frac{\varepsilon_1 \sigma x_2}{2\varepsilon_2 x_1 + \varepsilon_1 x_2} \tag{3}$$

Therefore, the variation in the charge density on the electrodes ($\Delta\sigma_m$) can be expressed as a function of the thickness variation (Δx_1 and Δx_2) as:

$$\Delta\sigma_m = \frac{\partial \sigma_m}{\partial x_1}\Delta x_1 + \frac{\partial \sigma_m}{\partial x_2}\Delta x_2 = -\frac{2\varepsilon_1\varepsilon_2\sigma x_2}{(2\varepsilon_2 x_1 + \varepsilon_1 x_2)^2}\Delta x_1 + \frac{2\varepsilon_1\varepsilon_2\sigma x_1}{(2\varepsilon_2 x_1 + \varepsilon_1 x_2)^2}\Delta x_2 \tag{4}$$

The application of an external force deforms the structure, and the relationships between the resulting stresses and strains can be expressed as:

$$\frac{F}{A} = Y_1 \frac{\Delta x_1}{x_1} = Y_2 \frac{\Delta x_2}{x_2} \quad (5)$$

Where Y_1 and Y_2 is the elastic modulus of FEP film and polymer foam spacer, respectively and A is the area of the device.

By its definition, the piezoelectric coefficient can be expressed as:

$$d_{33} = \frac{\Delta\sigma_m}{F/_A} == -\frac{2\varepsilon_1\varepsilon_2\sigma x_1 x_2}{(2\varepsilon_2 x_1 + \varepsilon_1 x_2)^2 Y_1} + \frac{2\varepsilon_1\varepsilon_2\sigma x_1 x_2}{(2\varepsilon_2 x_1 + \varepsilon_1 x_2)^2 Y_2} \quad (6)$$

Eq. (6) can be simplified to

$$d_{33} = \frac{2\varepsilon_1\varepsilon_2\sigma x_1 x_2}{(2\varepsilon_2 x_1 + \varepsilon_1 x_2)^2}\left(\frac{1}{Y_2} - \frac{1}{Y_1}\right) \quad (7)$$

According to equation (7), the piezoelectric coefficient d_{33} of the FEP polymer foam ferroelectret structure is determined by the layer thickness (x_1 and x_2), elastic modulus (Y_1 and Y_2) and charge density (σ). For a given structure, the value of the layer thicknesses can be considered as constant and therefore the d_{33} coefficient only varies with the material properties. Equation 7 is a reciprocal function such that d_{33} increases as the elastic modulus of the polymer foam (Y_2) reduces.

To evaluate the ability of a piezoelectric material to generate electrical power from mechanical deformations, it is also necessary to determine the electromechanical coupling coefficient k_{33} [19]:

$${k_{33}}^2 = \frac{{d_{33}}^2}{{s_{33}}^E {\varepsilon_{33}}^T} \quad (8)$$

Where ${s_{33}}^E$ is the compliance of the FEP-porous polymer ferroelectret under constant electric field, and ${\varepsilon_{33}}^T$ is the permittivity for dielectric displacement and electric field in direction 3, under constant strain.

The piezoelectric voltage constant g is the electric field generated by a piezoelectric material per unit of applied mechanical stress. It can be expressed as [19]:

$$g_{33} = \frac{d_{33}}{{\varepsilon_{33}}^T} \quad (9)$$

3. Experimental detail

3.1 Preparation of FEP films and porous polymer

The FEP films (304 mm × 200 mm with thickness of 25 μm) were obtained from DuPont. These films are cut to a sample size of 50 mm × 50 mm. Aluminium electrodes were evaporated on to one side of the films (Bak600 Evaporator, Levbold Ltd.) The electrode has an area of 40 mm × 40 mm and a thickness of 100 nm. Seven types of polymer foams with different Young' modulus were purchased from eFoam. These foams were cut into as sample size of 10 mm × 10 mm × 1 mm.

3.2 Preparation of FEP-porous polymer ferroelectret

The schematic of the FEP-polymer foam ferroelectret fabrication process is illustrated in Figure 3. A thin layer of double sided adhesive tape was patterned and attached to the side of the FEP film without the electrode. Then, the thin piece of polymer foam was placed in the central area where the FEP film was not covered by the adhesive film. To seal the entire structure, the other layer of FEP film was attached to the other side of the adhesive film. The ferroelectret was then charged by placing it in a high electric field using a corona poling rig. A corona-tip voltage of -30 kV and a charging time of 60 seconds was employed [20].

3.3 Samples Characterization

To investigate how the properties of the FEP-porous polymer ferroelectret are affected by the elastic modulus of the different polymer foams, the d_{33} coefficient of the ferroelectrets were measured using a PiezoMeter (PM300, Piezotest Ltd). For monitoring the long-term piezoelectric properties, all samples were stored at room temperature and under normal atmospheric condition. For each FEP polymer foam ferroelectret, three samples were investigated with each sample being measured 5 times in different locations. In addition, the dielectric constant parameters were measured by an impedance analyse (6500B, Wayne Kerr).

An Instron electrodynamic instrument (ElectroPuls E1000, Instron Ltd) was used for determining the mechanical properties of the polymer foams. A force of 10 N was applied to the polymer foam sample in the thickness direction and the deformation measured. It also was used to evaluate the suitability of the FEP-polymer foam ferroelectret for kinetic energy harvesting and measuring the amount of the output power in the d_{33} mode. An applied a force of 350 N with a ramp rate of 11000 N/s was applied at a frequency of 1 Hz on the test samples and an oscilloscope was used to record the voltage generated across a variable load resistor. This enabled the instantaneous the power output profile to be determined. The FEP polymer foam ferroelectret was also used to charge a capacitor via a rectifier circuit, and this provides a measurement of the average power delivered considering the power conversion circuit.

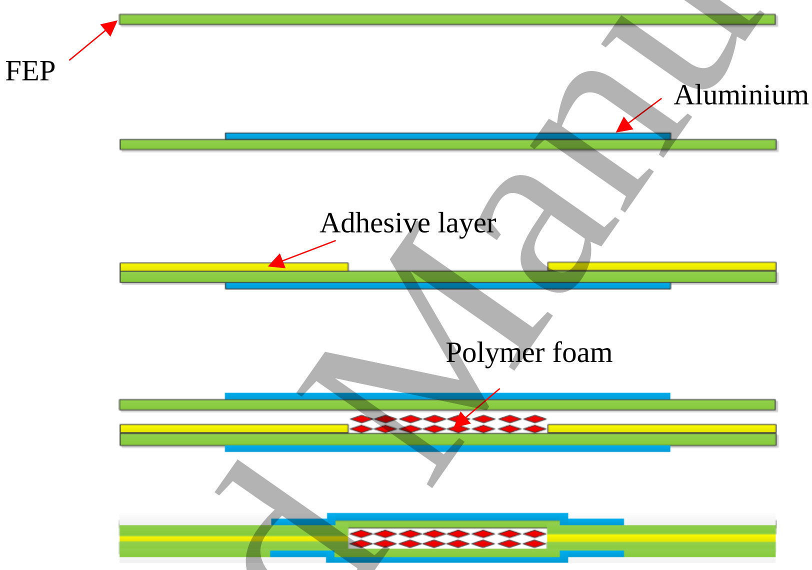

Figure 3. The schematic of FEP-polymer foam ferroelectret fabrication processes

4. Results and discussions

In order to characterize Young's modulus of the seven porous polymer, stress-strain tests were performed by the Instron E1000. The results were compared with the piezoelectric properties of the seven ferroelectret, as shown in Figure 4 (a). The Young's modulus of these porous polymer samples was calculated from the expression:

$$Y = \frac{FL}{A\Delta L} \tag{10}$$

Where F is the force applied to the sample in the thickness direction, A is the area of the cross section perpendicular to the applied force, ΔL and L is the change in length and original length of the sample, respectively.

Eq. (6) could be used to estimate the value of d_{33}. Due to no significantly difference among the measured dielectric constant of these sample, taking ε_1=2, ε_2=2.1, σ=150 μC/m^2, Y_1=480 MPa, based on the measured Young's modulus of porous polymer foam. The theoretically calculated d_{33} for these FEP-porous polymer ferroelectret are list in Table 1. It can be observed that as the Young's modulus of the foam spacer increases, the generated peak output voltage and measured piezoelectric coefficients d_{33} decreases. The reason is that the lower the foam's Young's modulus, the greater the deformation and the higher macroscopic dipole moment variation for a given applied force resulting in higher piezoelectric coefficients d_{33}. There are some obvious difference between the theoretical and practical piezoelectric coefficients, it still shows reasonable agreement and confirm the theoretical prediction that a lower foam Young's modulus increases the d_{33} coefficient. For the lower Young's modulus polymer foam, the mathematical model overestimates the d_{33} value because it only considers the Young's modulus of the foam and does not include the Young's modulus of the trapped volume of air. The trapped volume of air will increase the stiffness of the device in practice leading to a lower d_{33}. For higher stiffness polymer foams, the model had under estimated the d_{33}. The higher stiffness foams have a smaller void structure and it is believed the voids within the foam become charged during the poling process. This contributes to the measured d_{33} but since the foam is not a stable electret material, this charge is not maintained. Measurements of d_{33} after period of 30 days were performed to test this theory and the d33 of the higher stiffness FEP-porous polymer ferroelectrets fell by 27% and is much closer to the modelled value. For the lower stiffness FEP-porous polymer ferroelectrets, the voids in the foam are much larger and fewer and contribute less to the initial charge within the device and the measured d33 showed a decline of 8% after 30 days. Figure 4 (a) shows a plot of the d_{33} and peak output voltage versus Young's modulus for the 7 foams. The maximum peak output voltage was 8 V and piezoelectric coefficient d_{33} 1000 pC/N and these were obtained from the most compliant FEP-polymer foam ferroelectret. The output voltage of a FEP-polymer foam ferroelectret under the 350 N cyclical compressive force takes the form of a voltage pulses as shown in Figure 4 (b) and from this the peak power was calculated to be 6.4 μW which equates to a peak power density of 62.4 μW/cm^3.

Table 1. A summary of the measured Young's modulus and theoretically calculated values for these seven FEP-porous polymer ferroelectret

	Measured Young's modulus of porous polymer foam (Pa)	Measured Young's modulus of ferroelectret (MPa)	Theoretical piezoelectric coefficient d_{33} (pC/N)	Measured piezoelectric coefficient d_{33} after charging (pC/N)	Measured piezoelectric coefficient d_{33} at 30 days after charging (pC/N)	Calculated Coupling factor k_{33} (using measured d_{33})	Theoretical Piezoelectric voltage constant g_{33} (V×m/N)
Antistatic foam	5786	1.1	1228	1092	1010	0.24	56
Memory foam	6958	1.2	1021	895	845	0.23	45
Plastazote foam	7469	1.3	951	798	760	0.21	36
Medium foam	14004	3.1	507	502	496	0.20	14
Acoustic flat foam	18051	4.2	393	401	382	0.19	9
High firm foam	25745	5.1	276	349	285	0.18	7
Reflex superior firm foam	34166	6.3	208	297	218	0.17	5

Table 1 also shows the theoretical electromechanical coupling factor (k_{33}) (estimated by Eq. 8) and theoretical piezoelectric voltage constant (g_{33}) (calculated from Eq. 9) for these seven FEP-porous polymer ferroelectrets. From this table, the highest electromechanically coupling factor and piezoelectric voltage constant are obtained by the FEP-porous polymer ferroelectret with the lowest Young's modulus. The FEP polymer foam ferroelectret have extremely high g_{33} in comparison to all the other piezoelectric materials: PZT (0.01), PVDF (0.2) and PP (30) [21-22]. The calculated coupling factor k_{33} using measured d_{33} values is not as high as the bulk ceramic PZT (~0.7), but is higher than the other polymer materials PVDF (0.1-0.15) and PP (0.08) [21-22].

The negative output pulses are produced by the deformation of the sample when the compressive force is released and the magnitude of the negative output voltage is much less than the positive output voltage. This can be explained by considering the duration of force applied. As mentioned in section 2, the generated charge is directly proportional to the macroscopic dipole moment variation, which is caused by the deformation of the sample. Hence, the generated output voltage can be expressed as:

$$V = \frac{\Delta Q}{t} R \tag{11}$$

Where V is the output voltage, ΔQ is the variation of charge, t is the time and R is the load resistance. For the positive peak, from Eq. (11), the peak voltage is directly proportional to the ramp rate of the applied force, which is controlled by the ElectroPuls E1000. In contrast, for the negative peak, the duration of deformation after the load is released is mainly determined by the elastic properties of polymer foam. The effective ramp rate is therefore lower that when the force is applied and therefor the peak negative voltage is less than the positive peak.

The electrical energy generated by the sample can be calculated using the formula:

$$U = \int_{t_1}^{t_2} \frac{V(t)^2}{R} dt \tag{12}$$

From Figure 4 (b), the electric energy generated from the sample is approximately 0.8 μJ/per cycle. The effective energy per cycle applied on the sample can be caudated by multiplying force by deformation and time, is approximately 69.1 μJ. Hence, the practical coupling factor is 0.107 that is much lower than the theoretical value.

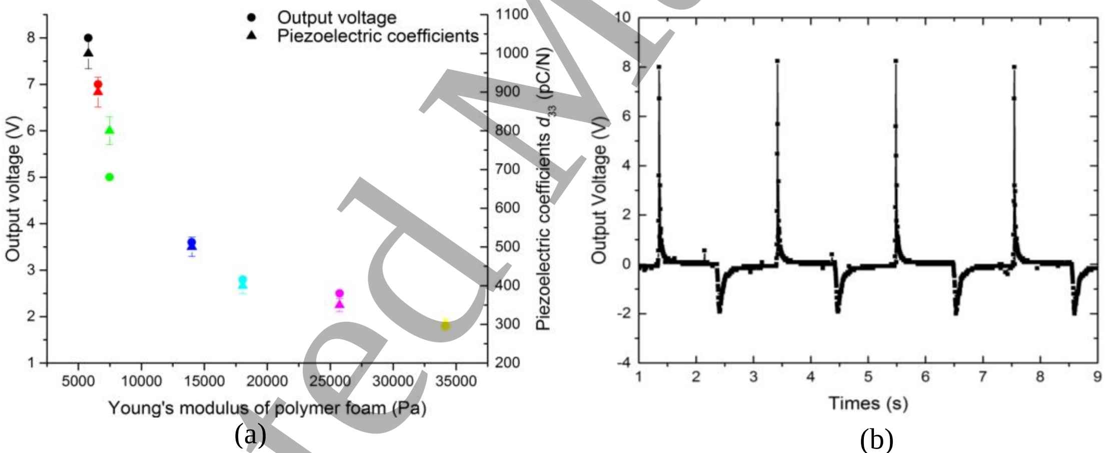

Figure 4. (a) The generated peak output voltage and measured piezoelectric coefficient d_{33} for the seven different FEP-porous polymer ferroelectrets, plotted against the polymer foam's Young's modulus, (b) Output voltage of FEP-porous polymer ferroelectret under cyclical 350 N compressive force with 10 MΩ load.

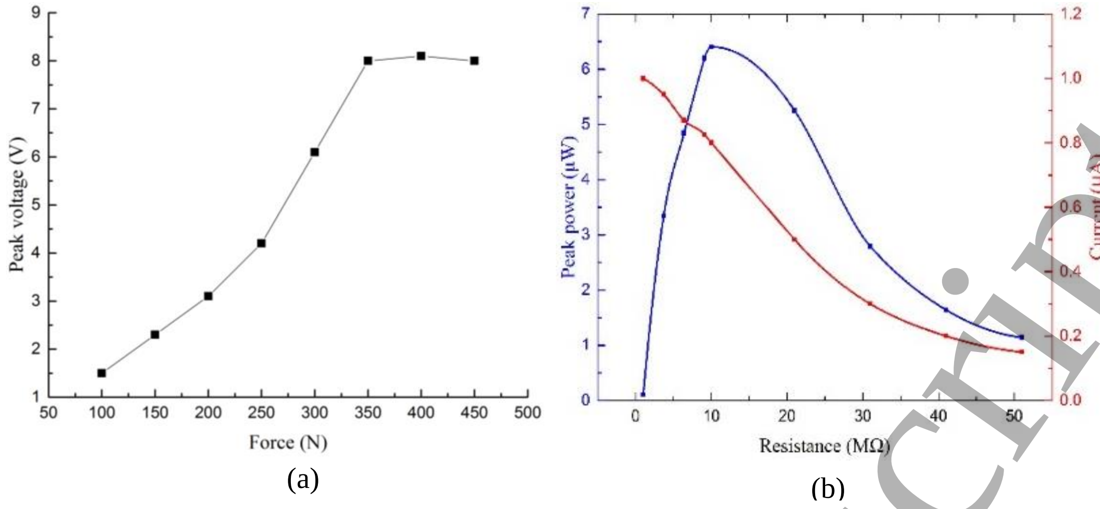

Figure 5. Output characterization of the FEP porous polymer ferroelectret. (a) The output peak voltage under different force. (b) Output current and instantaneous output power as a function of the load resistance

Figure 5 (a) shows the output performance of the FEP polymer foam ferroelectret under differernt compressive forces. The output peak voltage increases with the increasing force and saturates at around 350 N at which point the foam spacer has been fully compressed. The peak output voltage maintains a constant value for forces beyond 350 N, since the deformation will remain constant. The output current and power versus resistance is shown in Figure 5 (b). Maximum output power occurs at a load resistance of 10 MΩ, with a peak power of 6.4 μW. The long-term stability of the FEP-polymer foam ferroelectret is shown in Figure 6. The d_{33} coefficient drops by 8% of its initial value after around 13 days and after this remains constant up to 30 days.

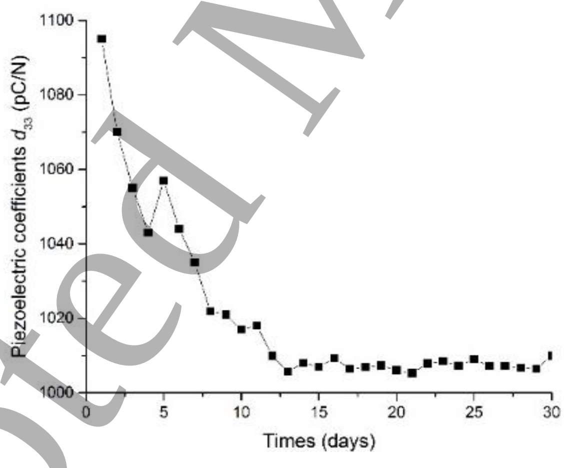

Figure 6. Piezoelectric coefficients d_{33} decay cures for 30 days

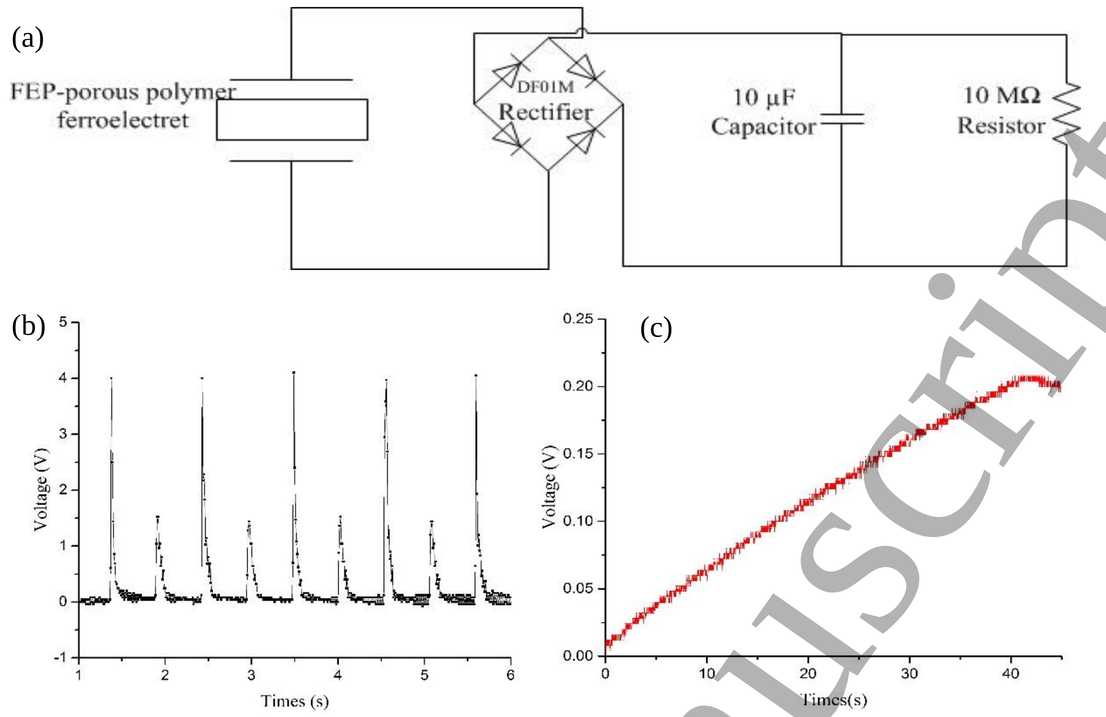

Figure 7. (a) Circuit diagram of the ferroelectret harvester, rectifier and energy storage. (b) Output voltage pulses after rectification under 350 N compressive force with a frequency of 1 Hz. (c) Capacitor charging curve up to 45 seconds

To explore the practical energy harvesting potential of the FEP-polymer foam ferroelectret, it was connected to a capacitor through a commercial bridge rectifier (DF01M) consisting of four diodes, as shown by the equivalent circuit in Figure 7 (a). The ferroelectret was tested under a cyclical load of 350 N compressive force at 1 Hz and the rectified voltage output is shown in Figure 7 (b). According to Eq. (12), the electric energy through the bridge rectifier is approximately 0.19 μJ/per cycle, which is about a quarter of the energy generated from the sample. The voltage across the 10 μF capacitor increases to 0.2 V after 40 seconds as shown in Figure 7 (c). The energy delivered to the capacitor each cycle can be calculated with the total energy accumulated during the entire charging process of 0.2 μJ (40 cycles in total), corresponding to an average energy of 5 nJ/cycle, or 5 nW. The average power output is far less than the electric energy trough the bridge rectifier. This is due to the effect of the impedance mismatch between the rectifying circuit and the optimal resistive load, the voltage drop of diodes and the high ramp speed/low frequency, which means no output is generated for large parts of the output trace shown in Figure 7 (b).

5. Conclusions

In this work, a low cost and rapid fabrication method for ferroelectret has been reported. It enables the rapid formation of a ferroelectret from a stable polymer electret film (FEP) utilizing any compressive polymer material as mechanical spacer. Due to the materials involved and the device dimensions, it is a lightweight and flexible assembly very well suited to wearable electronics. The piezoelectric properties of the fabricated FEP polymer foam ferroelectret are maximised by utilizing a spacer material with lowest Young' modulus. The piezoelectric properties of the FEP polymer foam ferroelectret were found to stabilise after 13 days providing a stable long-term ferroelectret solution under typical indoor conditions. The lowest Young's modulus spacer foam results in a maximum peak output voltage of 8 V when compressed by 350 N equating to a peak output power of 6.4 μW when connected to a 10 MΩ resistive load. The maximum practical coupling factor k_{33} of the sample is achieved as 0.107, which is almost one third of the theoretical calculated value. This output can be rectified and used to charge a storage capacitor and in this case provides an average output power of 5 nW after rectification when compressed at a frequency of 1 Hz. Further work to improve this includes investigating spacer materials that increase the pulse duration potentially increasing the energy output and optimising the rectifier circuit. This fabrication method can also be used with other soft mechanical spacer materials such as fabrics making it potentially suitable for integrating into e-textile devices.

Acknowledgments

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Reference

[1] H. Chen , Z. Su , Y. Song , X. Cheng , X. Chen , B. Meng , Z. Song , D. Chen , and H. Zhang,Adv.Funct.Mater. 27, 1604434 (2017). https://doi.org/10.1002/adfm.201604434,
[2] J. Han, B.Kim , J. Li, and M. Meyyappan, Appl. Phys. Lett. 102, 051903 (2013). https://doi.org/10.1063/1.4790437
[3] P. D. Mitcheson, E. M. Yeatman, G. K. Rao, A. S. Holmes, and T. C. Green, ‘‘Energy harvesting from human and machine motion for wireless electronic devices,’’ Proc. IEEE, vol. 96, no. 9, pp. 1457–1486, Sep. 2008.
[4] N. S. Shenck and J. A. Paradiso, “Energy scavenging with shoe-mounted piezoelectrics,” IEEE Micro, vol. 21, no. 3, pp. 30–42, 2001.
[5] Dagdeviren C, et al. Conformal piezoelectric energy harvesting and storage from motions of the heart, lung, and diaphragm. Proc Natl Acad Sci, USA. 2014;111:1927–1932.
[6] T. J. Kazmierski and S. Beeby. (2011). “Energy harvesting systems principles, modeling and applications,” Available: http://lib.myilibrary.com?id=297276
[7] G. M. Sessler, "Charge distribution and transport in polymers", IEEE Trans. Dielectr. Electr. Insul, Vol. 4, No.5, pp. 614-628, 1997.
[8] Mohebbi, A., et al. (2016). "Cellular Polymer Ferroelectret: A Review on Their Development and Their Piezoelectric Properties." Advances in Polymer Technology: n/a-n/a.
[9] S. Bauer, R. Gerhard-Multhaupt, and G.M. Sessler, ”Ferroelectrets: Soft electroactive foams for transducers,” Physics Today vol. 57, no. 2, pp. 37-43, 2004Another reference
[10] Paajanen M, Wegener M and Gerhard-Multhaupt R 2001 Understanding the role of the gas in the voids during corona charging of cellular electret films—a way to enhance their piezoelectricity J. Phys. D: Appl. Phys. 34 2482–8J. Hillenbrand and G. M. Sessler, “Piezoelectricity in cellular electret films”, *IEEE Trans. Dielect. Electr. Insul.*, vol. 7 (4), pp. **537-542**, 2000.
[11] Shi. J, Zhu. D and Beeby. S.P. An investigation of PDMS structures for optimized ferroelectret performance. Journal of Physics: Conference Series , 557, 012104. 2014.
[12] M. Paajanen, J. Lekkala, and K. Kirjavainen, “Electromechanical film (EMFi) - a new multipurpose electret material”, Sens. Actu. A: Phys., vol. 84 (1-2), pp. 95-102, 2000.
[13] I. Graz, M. Kaltenbrunner, C. Keplinger, R. Schwödiauer, S. Bauer, S. P. Lacour, and S. Wagner, “Flexible ferroelectret field-effect transistor for large-area sensor skins and microphones”, Appl. Phys. Lett., vol. 89 (7), no. 073501, 2006.
[14] M. Paajanen, H. Välimäki, and J. Lekkala, “Modelling the sensor and actuator operations of the ElectroMechanical Film EMFi”, Proceedings, 10th International Symposium on Electrets, 22-24 September 1999, Delphi, Greece (IEEE Service Center, Piscataway, NJ, USA 1999), pp. 735-738.
[15] G. M. Sessler and J. Hillenbrand, “Electromechanical response equations of cellular electret films”, Proceedings, 10th International Symposium on Electrets, 22-24

September 1999, Delphi, Greece (IEEE Service Center, Piscataway, NJ, USA 1999), pp. 261-264.
[16] X. Zhang, J. Hillenbrand, and G. M. Sessler, "Improvement of piezoelectric activity of cellular polymers using a double-expansion process", J. Phys. D: Appl. Phys., vol. 37, pp. 2146-2150, 2004.
[17] J. Hillenbrand, G. M. Sessler, and X. Zhang, "Verification of a model for the piezoelectric d33 coefficient of cellular electret films", J. Appl. Phys., vol. 98 (6), no. 064105, 2005.
[18] P. Zhang, Z. Xia, X. Qiu, F. Wang, and X. Wu, "Influence of charging parameters on piezoelectricity for cellular PP film electrets", Chin. Phys. Soc., vol. 55 (2), pp. 904-909, 2006.
[19] APC International, L. (2002). "Piezoelectric Ceramics: Principles and Applications," APC International.
[20] von Seggern H, Zhukov S, Fedosov S. "Importance of Geometry and Breakdown Field on the Piezoelectric d_{33} Coefficient of Corona Charged Ferroelectret Sandwiches." IEEE Trans Dielectrics Electr Insul 2011; 18(1): 49-55
[21] Heywang, W., et al. (2008). "Piezoelectricity: Evolution and Future of a Technology," Springer Berlin Heidelberg.
[22] Priya, S. and D. J. Inman (2008). "Energy Harvesting Technologies," Springer US.