

Energy Harvesting Study on Single and Multilayer Ferroelectret Foams under Compressive Force

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ABSTRACT

Cellular polypropylene (PP) ferroelectret is a thin and flexible cellular polymer foam that generates electrical power under mechanical force. This work investigates single and multilayer ferroelectret PP foams and their potential to supply energy for human-body-worn sensors. Human foot-fall is emulated using an electrodynamic instrument, allowing applied compressive force and momentum to be correlated with energy output. Peak power, output pulse duration, and energy per strike is derived experimentally as a function of force and momentum, and shown to be a strong function of external load resistance, thus providing a clear maximum energy point. The possibility of increasing pulse time and reducing voltage to CMOS compatible levels at some expense of peak power is shown. To further increase the output power, multilayer ferroelectret is presented. The synchronized power generation of each layer is studied and illustrated using simulation, and results are supported by experiments. Finally, the energy output of single-layer and multi-layer ferroelectrets are compared by charging a capacitor via a rectifier. A ten-layer ferroelectret is shown to have charging ability 29.1 times better than that of the single-layer ferroelectret. It demonstrates energy output that is capable of powering the start-up and transmission of a typical low-power wireless sensor chipset.

Index Terms — Ferroelectret, energy harvesting, polypropylene (PP), single layer, multilayer, compressive force.

1 INTRODUCTION

FERROELECTRET is a thin and flexible cellular polymer foam that can store charges in its internal voids [1-4], thus being able to generate electric pulse under mechanical deformation such as compression and bending [5-6]. Due to its high piezoelectric voltage constant g_{33} [7], ferroelectret has already been used extensively in sensor applications, such as blood pressure pulse transducer [8], touch sensor [9], ultrasonic transducer [10], prosthetic skin [11], and accelerometer [12]. Among the ferroelectret materials that have been developed, cellular polypropylene (PP) is one of the most researched [2-6], and being one of the first commercialized ferroelectrets [13-15]. Charged cellular PP exhibits a high piezoelectric charge constant d_{33} , which is comparable to commercial PZT [7]. It is very soft in the thickness direction, with Young's modulus in the order of 1MPa [16-17]. Due to its high d_{33} and small Young's modulus, PP is able to

generate large electric pulse under compression force.

Energy harvesting technology that harvests power from human motion has received growing attention over the last decade. This technology enables the low-power electronics, such as wireless sensor, to be operated using the power that harvested from human activities, thus eliminates the need of recharging, and allow the devices to be self-sustainable [18-19]. The energy harvester that harvests kinetic energy from human motion is usually based on the piezoelectric effect that converts mechanical energy to electrical energy [18]. The most common piezoelectric materials used in kinetic energy harvester are lead zirconate titanate (PZT) and polyvinylidene fluoride (PVDF) [7, 18-20]. The piezoelectric effect of PZT is based on the distortion of its perovskite unit cell under mechanical deformation [21-22]. Being a piezoceramic, even though PZT has relatively high d_{33} , the applications of this material in wearable energy harvester have been limited by its high Young's modulus and brittle ceramic nature. PVDF, on the other

hand, its piezoelectric effect comes from the change in the density of the molecular dipoles under mechanical deformation [7]. Despite the small Young's modulus of PVDF, which makes it easy to deform, its d_{33} is an order of magnitude lower than PZT [7, 18]. Comparing to these two piezoelectric materials, charged cellular PP is light, thin, soft, and with relatively high d_{33} that is comparable to PZT. These properties make ferroelectret PP a promising candidate for using as the piezoelectric material in wearable energy harvester, to harvest power from human motion.

Previous studies have already investigated the vibration-based energy harvesting of single-layer and stacked ferroelectret PP, and focusing on the maximum power output at resonance frequency [23-24]. In this work, we are focusing on the energy harvesting ability of ferroelectret PP at low frequency compression, and with large compressive forces to resemble the pressure from human walking. Due to the soft polymer nature and high d_{33} of ferroelectrets, the most effective way to harvest energy from them is to apply compressive force on the materials in the thickness direction. As the compressive forces by human motion mainly come from walking, it is sensible to install the ferroelectrets in the insole to harvest power. Energy harvesting using shoe-mounted piezoelectric materials have been investigated by a number of research groups [25-28]. In our work an electrodynamic test instrument is used to resemble the compressive force and frequency from footstep, as well as quantifying them, thus being able to quantitatively correlate the ferroelectrets' output energy to the force resembled human walking. The multilayer ferroelectret PP foams are also investigated in this work. The small Young's modulus of these materials allows them to be largely deformed, thus be able to generate high voltage under compressive force, but with a small current due to their dielectric material nature [23]. Multilayer ferroelectret can boost the total power output by increasing the generated voltage [29-31] or the generated current, depending if the layers are connected in series or in parallel. However, the simulation and the experimental results in this work show that the deformation and output electric pulses of each layer in the multilayer structure can be asynchronized and thus affect the total energy output. The bonding between layers is important to synchronize their deformation and increase the total power output. A synchronized ten-layer ferroelectret PP demonstrates 29.1 times the charging ability of the single-layer PP, showing energy output that is capable of powering low-power wireless sensor chipset.

In the following sections, the output pulses of ferroelectret PP under compressive force are characterized by varying the external load resistances. Then the effects of applied force and momentum on the energy output are discussed. The output pulses of single-layer ferroelectret in different walking conditions, and their negative to positive pulse ratio are shown. Also, the synchronized pulse generation of each layer in multilayer ferroelectret is studied by simulation and illustrated by experiments.

Finally, the energy output of single-layer and multilayer ferroelectret PP are compared.

2 EXPERIMENTS

2.1 SAMPLE PREPARATION

The ferroelectret PP foams were commercially purchased from Emfit Ltd. The foams were manufactured by stretching the original polyolefin material in two perpendicular directions in a continuous biaxial orientation process, then further expanded in thickness at high-pressure gas-diffusion-expansion process [32-33]. The electric charges that stored in the foams were generated by the corona charging process which involves charge separation as a result of air breakdown within the microvoids. These commercial samples were sheets in the size of 230 mm \times 210 mm, with thickness of 70 μ m. Their piezoelectric charge constant d_{33} was measured using a PiezoMeter (PM300, Piezotest Ltd). The d_{33} value was determined to be approximately 300 pC/N.

The PP foams were further cut into testing samples with size of 60 mm \times 70 mm. For energy harvesting, electrodes were deposited on both sides of the samples by using a screen printer (Dek 248, Dek Printing Machines Ltd). The printing solution was silver Fabinks TC C4001 from Smart Fabric Inks Ltd. Ag electrodes with area of 50 mm \times 60 mm were printed on both sides of the PP foams, and then the samples were cured in an oven at a temperature of 50 $^{\circ}$ C for 10 minutes, to allow the silver paste to solidify. The cross-section of the PP foam with screen printed Ag electrode is shown by the SEM image in Figure 1. The multilayer PP foams was fabricated by bonding individual layers together using Tesa double sided bonding tapes. The electrodes of each layer were connected in parallel.

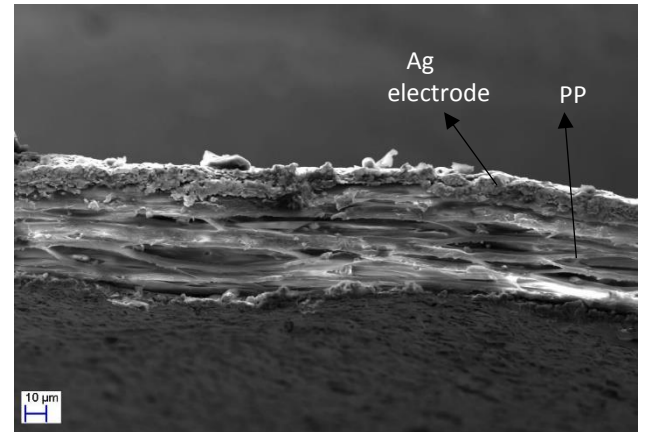


Figure 1. SEM image of a PP foam with screen printed Ag electrodes showing the cross-sectional structure.

2.2 QUANTIFICATION OF COMPRESSIVE FORCES AND ENERGY OUTPUT

To apply compressive forces resembling human walking, an Instron electrodynamic instrument (EletroPuls E1000, Instron Ltd) was used to quantify the applied forces. Average human walking has step frequency ranged from 0.4 to 1.45 steps/s for one foot [34-36]. By considering

the force simulation of the Instron ElectroPuls instrument, the compressive forces that applied on the tested samples were characterized into three types of wave functions as shown in Figure 2, in order to resemble the slow walking, normal walking and fast walking of human motion. Each walking mode has a maximum force of 800 N. The slow walking mode has step frequency of 0.4 steps/s, with each step holding at maximum force for a duration of 1 s. The normal walking mode has step frequency of 0.8 steps/s, with each step holding at maximum force for a duration of 0.5 s. The fast walking mode has step frequency of 1.25 steps/s, with each step holding at maximum force for a duration of 0.3 s.

The output voltages of the PP foams under compressive force were recorded using an oscilloscope (TDS2014, Tektronix UK Ltd). The charging of a capacitor by compressing the PP foams was measured using a data logger (KUSB3102, Keithley Instruments Ltd).

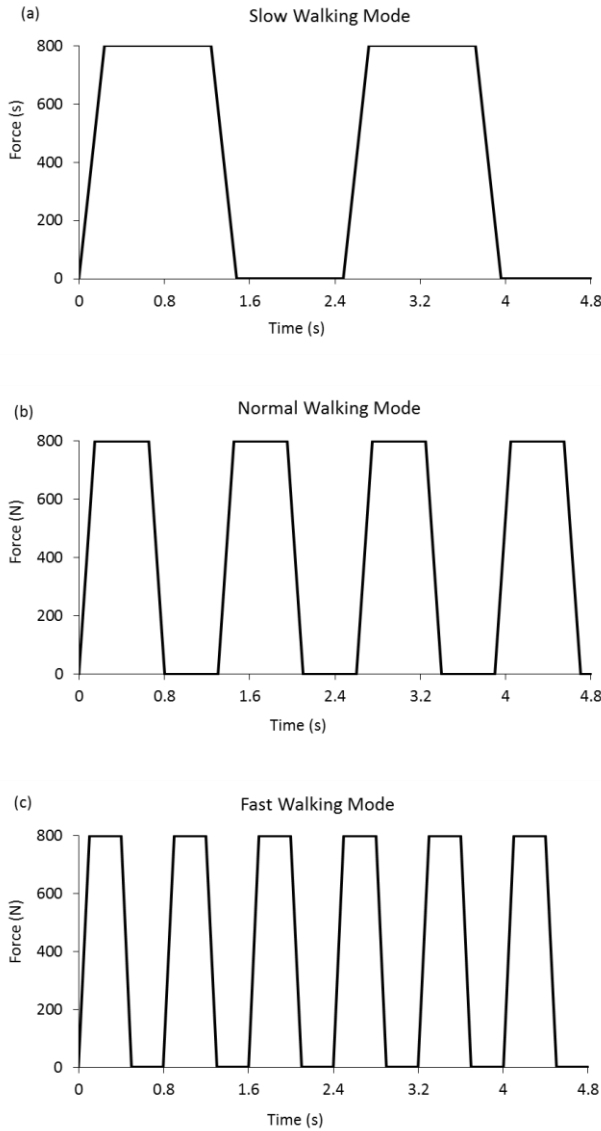


Figure 2. Wave functions of applied compressive force in slow walking mode (a), normal walking mode (b) and fast walking mode (c).

3 RESULTS AND DISCUSSION

3.1 CHARACTERIZATION OF ENERGY OUTPUT

The energy output of the ferroelectret PP foams under compressive force takes the form of a voltage pulse, as shown in Figure 3. The material is characterized by measuring the output voltage pulses, whilst scanning load resistance from 100 k Ω to 1 G Ω , as shown in Figure 4. It shows the measured peak voltage of a single-layer PP foam under compressive forces that are applied in normal walking mode, as a function of load resistance. The voltage values used in Figure 4 are the average of measured peak voltages from three consecutive pulses. The inferred peak current increases within the range of 0.1 to 1 M Ω , until it reaches a maximum value at 1 M Ω , then decreases with increasing load resistance, due to the Ohmic loss [37-38]. The voltage increases with increasing load resistance. Consequently, the peak power output ($W = IV_{peak}$) reaches the maximum value of 168 μ W, at a loading of 79.2 M Ω , as shown in Figure 4. This is corresponding to area unit power output of 5.6 μ W/cm², and volume unit power output of 800 μ W/cm³.

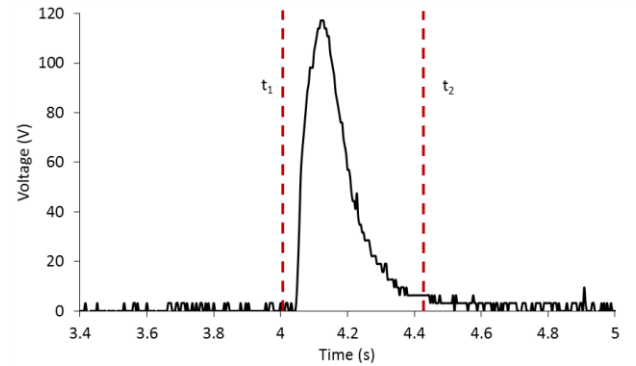


Figure 3. Energy output pulse of single-layer ferroelectret PP at the optimal resistance of 79.2 M Ω .

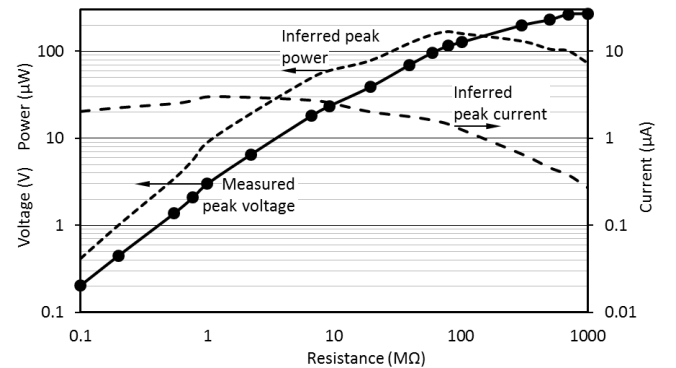


Figure 4. Measured peak voltage of output pulse of a single-layer PP foam under compressive force in normal walking mode, against resistance of purely resistive load inferred peak current and power.

The duration of the output pulses, indicated as $\Delta t = t_1 - t_2$ in Figure 3, are also influenced by the resistive load, as shown in Figure 5a. The pulse duration increases from 0.147 to 1.176 s as the load is swept from 0.1 to 1 G Ω . Therefore, at the optimal loading of 79.2 M Ω , where the

instantaneous power reaches a maximum value, the duration of output pulse is approximately 0.416 s, as shown in Figure 3. The electric energy generated by the ferroelectret can be calculated using the formula [37, 39]:

$$E = \left| \int_{t_1}^{t_2} V(t) \cdot I(t) dt \right| \quad (1)$$

Thus in Figure 3, the electric energy generated in normal walking mode is approximately 35.1 μJ per pulse, corresponding to area unit energy output of 1.17 $\mu\text{J}/\text{cm}^2$, and volume unit energy output of 167 $\mu\text{J}/\text{cm}^3$. Using equation (1), the output energy at different resistive loads is shown in Figure 5b. It indicates that unlike peak power, the maximum energy occurs at the resistance of 500 M Ω . At this resistance, the electric energy generated in normal walking mode is approximately 58.4 μJ per pulse, with area unit energy output of 1.95 $\mu\text{J}/\text{cm}^2$, and volume unit energy output of 278 $\mu\text{J}/\text{cm}^3$. This is corresponding to an average power output of 93.44 $\mu\text{W}/\text{s}$.

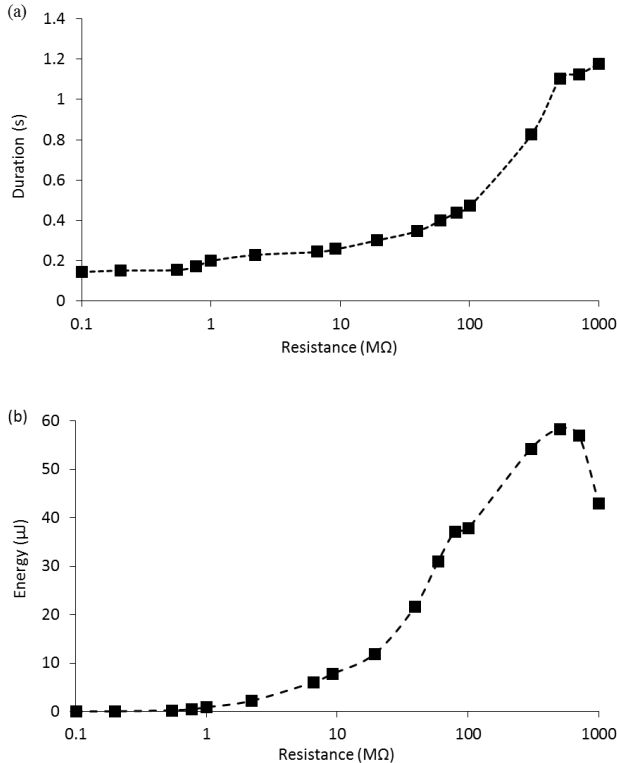


Figure 5. (a) Duration of output pulses at different resistive loads. (b) Output energy at different resistive loads.

The load resistance for maximum energy output is 500 M Ω . However at this load impedance, the peak voltage is in excess of 200 V, which leads on to the following considerations: In energy harvesting applications where the energy is extracted in pulses, it is preferable that the power management circuit is input-powered [40]. Comparing to powering from the system energy storage, the advantage of input-powering is that the power management circuit is active only during the energy pulse, thus minimizes the overall quiescent losses. However, the power losses of the power management circuit are strongly influenced by the supply voltage [41-42].

Therefore, such high voltage may not be desirable for electronic circuit. It may also be desirable to increase the pulse width at the expense of energy content in order to reduce the intermittency, which in itself causes system energy loss during start-up, as shown in [43]. In addition, as many integrated circuits only work safely under a voltage stress of 5.5 V, and a high external resistive load to the materials will make the matching from power converter being difficult in the CMOS process, it is more suitable to have output voltage in the range of 1 to 5.5 V. At 1 M Ω and in normal walking mode, the output peak voltage is 3 V and its instantaneous current is 3 μA , which, once rectified and smoothed, and possibly with some voltage clamping, would be suitable to be used directly as the supply to electronic circuits. Thus 1 M Ω is used as the resistive load in the following measurements.

3.2 FACTORS THAT AFFECT THE ENERGY OUTPUT

The maximum compressive force applied on the ferroelectrets in this work is set to be 800 N, roughly resembling a walking person with weight of 80 kg. The effect of a person's weight on the energy output is investigated in this work by varying the quantities of compressive forces in normal walking mode. Figure 6 shows the change of peak output voltage at different applied forces, with load resistance of 1 M Ω . The fitted line indicates that the output voltage increases linearly with increasing forces, at a rate of 3.6 mV/N. The durations of output pulses remain constant with increasing applied forces. For average body weights in different age groups [44], the output voltages are within the range of 1 to 5.5 V, which is suitable to power the electronic circuits directly.

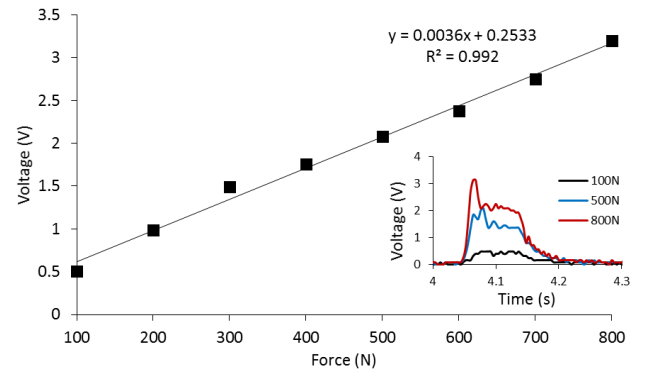


Figure 6. Peak output voltage at different applied compressive forces.

Another factor that affects the energy output is the momentum of applied compression. Figure 7 shows the output pulses of compressions applied at different momentums, with 800 N of maximum force. These momentums are calculated by $p=mv$. Velocity v is recorded by the instrument as the speed of the compressor. At the moment when the force reaches 800 N, the mass m can be considered as 80 kg, being similar to a static force of 800 N. A compression with high momentum produces an output pulse with high voltage, but with smaller

duration than those ones with smaller momentum. For example, in slow walking mode, the compressor is applied at a speed of 7 mm/s, resembling a foot stepping on the ground with momentum of 0.56 kgms^{-1} . It produces a pulse with peak voltage of 1.8 V, with duration of 0.28 s. In normal walking mode, the compressor is applied with momentum of 0.88 kgms^{-1} , producing a pulse with peak voltage of 3.2 V and duration of 0.22 s. In fast walking mode, the compressor is applied with momentum of 1.2 kgms^{-1} , producing a pulse with peak voltage of 5.9 V and duration of 0.18 s. With momentum of 1.44 kgms^{-1} , the applied force can produce a pulse with high peak voltage of 10.7 V and duration of 0.16 s. This implies that during walking, the interval between each walking steps is longer than that of pulse duration. Thus there would be interval time at which no energy is harvested. However, if the forces are applied at a fast pace, in the case such as running, each step is applying on the ground with high momentum, producing pulses with high voltage. When the running pace is fast enough, such as at 6 Hz frequency for steps, the interval between steps is smaller than the duration of output pulse. Thus it is possible to reach a continuous power output with high voltage. These need to be taken into consideration when designing the power electronics for the energy harvester.

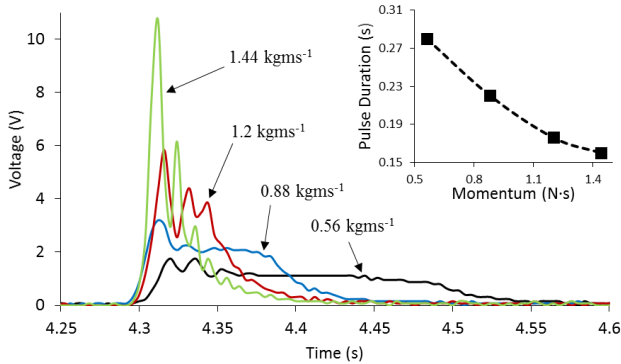


Figure 7. Output voltage pulse profiles and duration for four different momentums under a constant force of 800 N.

3.3 ENERGY OUTPUT OF SINGLE-LAYER FERROELECTRET

The outputs pulses of a single-layer PP foam under compressive forces in slow walking, normal walking and fast walking mode are compared in Figure 8. The load resistance used in obtaining these data is $1 \text{ M}\Omega$. It shows that a single-layer PP under 800 N of compressive force, can generate output pulse with peak power of $3.1 \text{ }\mu\text{W}$ and energy of $0.43 \text{ }\mu\text{J}$ in slow walking mode, with peak power of $10.2 \text{ }\mu\text{W}$ and energy of $1.12 \text{ }\mu\text{J}$ in normal walking mode, with peak power of $34.1 \text{ }\mu\text{W}$ and energy of $3.07 \text{ }\mu\text{J}$ in fast walking mode. Even though fast walking has shorter duration for an output pulse, it produces an energy output almost 3 times of that in normal walking mode, and 7 times of that in slow walking mode.

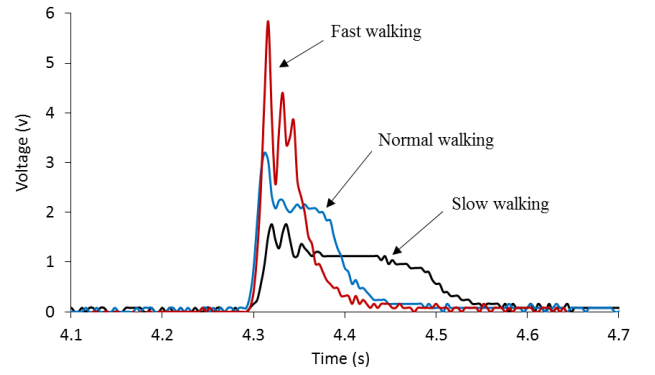


Figure 8. Output pulses of a single-layer PP foam in slow walking mode, normal walking mode and fast walking mode.

The output pulses and their rectified outputs of a single PP foam under one cycle of compressive force loading in normal walking mode are shown in Figure 9a. It indicates that the rectified output pulse can retain about 77% of the duration of the unrectified pulse. A cycle of compressive force loading produces one positive pulse when applying the force, and a negative pulse when releasing the force. As shown in Figure 9a, this negative pulse has size comparable to the positive pulse, thus produces a sizable rectified output.

However, this changes with momentum. Figure 9b shows the ratio between the peak voltage of negative pulse and the peak voltage of positive pulse at different momentums. It indicates that with high momentum, such as in fast walking mode, this ratio is less than that of normal walking and slow walking, which have lower momentum when the force is applying. This can be explained by considering the change of momentum. In these walking modes with maximum force of 800 N, the compressive forces can be considered as being from an 80 kg object dropping with a velocity. Between it just touching the sample and stopping completely, the change in velocity is Δv . According to the formula:

$$F = m \times a = m \times \frac{\Delta v}{\Delta t} \quad (2)$$

therefore,

$$\frac{F \times \Delta t}{m} = \Delta v \quad (3)$$

Δv varies with momentums, but Δt and m are the same in different walking modes. Thus the force F is directly proportional to Δv , and the impulse with higher momentum has higher value of Δv . As the peak voltage V of an output pulse is directly proportional to the applied force in a simplified mathematical model [6, 15, 45], the output voltage in a mode with high momentum is higher than those one with low momentum. This explains the difference in the positive output pulses in different walking modes. However, for the negative output pulses, which are produced by the deformation of the ferroelectret when releasing the compressive force, Δv is independent of the momentums from the compressive force. Thus the peak voltages of negative pulses are similar in different walking modes, leading to the

decrease of negative/positive peak voltage ratio as shown in Figure 9b.

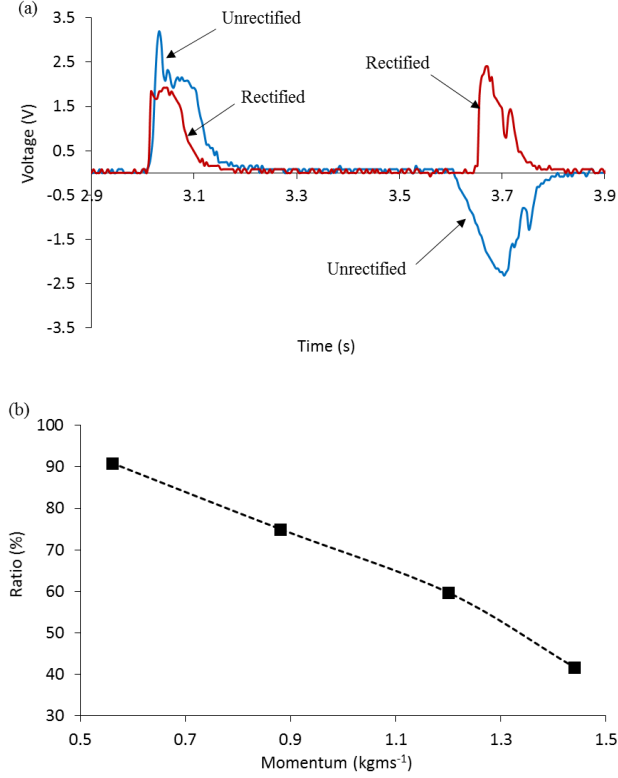


Figure 9. (a) Unrectified and rectified output pulses in normal walking mode. (b) Ratio of negative output peak voltage to positive output peak voltage at different momentums.

3.4 SYNCHRONIZATION OF MULTILAYER OUTPUT

A sensible method to improve the energy harvesting output of ferroelectrets is using the multilayer structure by stacking a number of PP foams together. By connecting these layers in parallel, the overall generated current can be increased. An important procedure in fabricating the multilayers foams is the bonding of layers. Figure 10 shows the simulation of elastic strain from a three-layer PP foams under 800 N of compressive force, with all edges in constraint condition. It indicates that the 1st layer (top layer), deforms more than the 2nd layer (middle layer), and the 2nd layer deforms more than the 3rd layer (bottom layer). As the output voltage is directly proportional to deformation [6, 45], which is the change of thickness in this case, this simulation implies that the 1st layer produces higher voltage than the 2nd layer, and the 2nd layer produces higher voltage than the 3rd layer.

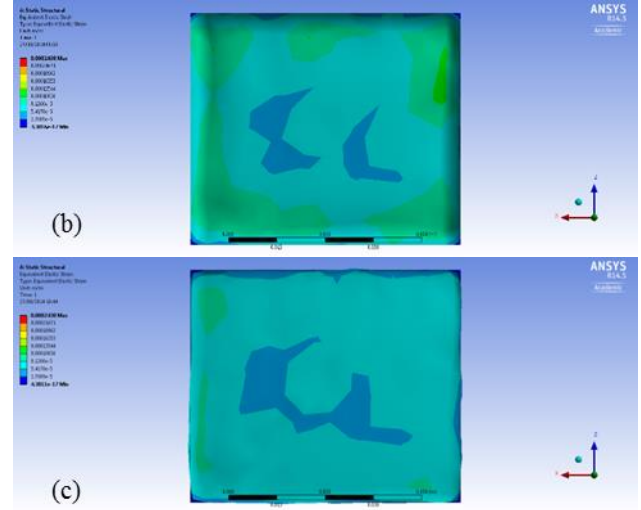
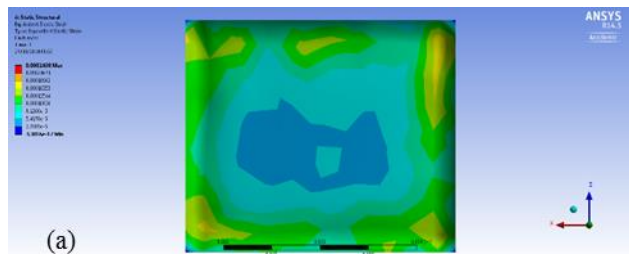


Figure 10. Simulation of elastic strain on 1st layer (a), 2nd layer (b) and 3rd layer (c) in a three-layer PP foams under 800N of compressive force

To support this simulation, a three-layer PP sample is fabricated by stacking the layers with all edges sealed. Insulating polymer films are inserted between the layers to prevent contact between positive and negative electrodes. Under a compressive force, the output pulses from each layer are shown in Figure 11a. It shows that the 1st layer produces peak voltage of 5.44 V, the 2nd layer produces 4.88 V, and the 3rd layer produces 3.2 V. This experiment result matches the prediction from simulation, implying that the output pulses are not synchronized if there is no bonding between the layers. This is the key reason for the bonding procedure in the fabrication of multilayer ferroelectrets. By bonding each layer together, the output pulses are shown in Figure 11b, which demonstrates a high level of synchronization.

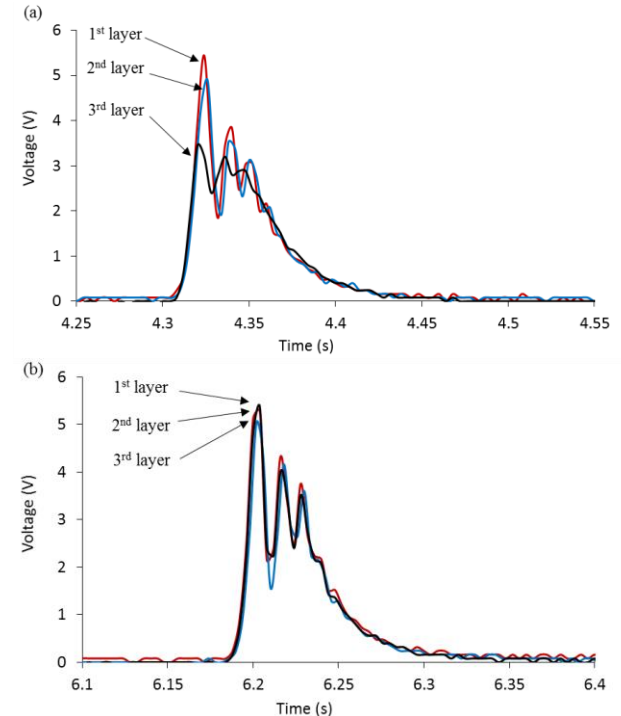


Figure 11. Output pulses from each layers in a three-layer PP foams under compressive force without bonding (a), and with bonding (b).

3.5 ENERGY OUTPUT OF MULTILAYER FERROELECTRET

In this work a ten-layer PP sample is fabricated to compare with the single-layer sample for energy output. In normal walking mode, with load resistance of 1 MΩ, the output pulses of the ten-layer and single-layer PP are shown in Figure 12 a. It shows that the ten-layer sample produces an output pulse with peak voltage of 10 V and a duration of 0.224 s. Thus its peak power is 100 μW and the energy output is 11.2 μJ, which are about 10 times of those from single-layer sample. This indicates that with bonding between layers, the energy output from multilayer ferroelectret increases almost linearly with the number of layers.

A direct comparison of the energy harvested from single- and ten-layer ferroelectret materials is shown in Figure 12b. The pulses are full-wave-rectified into a 2.2 μF capacitor, and the compressive forces are set to normal walking mode. The results show that the single-layer sample charges the capacitor to 0.87 V in 5 s, while the ten-layer sample charges the capacitor to 4.7 V in 5 s. The plotted capacitor energy is inferred from the voltage using

$$E = \frac{1}{2} CV^2 \quad (4)$$

Therefore, in normal walking mode, the unit energy produced by the single-layer sample from charging the capacitor is 0.167 μJ/s, whilst the ten-layer sample is 4.86 μJ/s, showing 29.1 times better of charging rate. Thus the ten-layer system starts up less than 10th of the time of the single-layer system. This is due to increased harvester utilisation at higher capacitor voltages (better impedance matching) and the increase in capacitor leakage with voltage.

The charging ability of the ten-layer sample is further increased if the compressive forces were applied in a fast walking mode, due the increase in the momentum of forces and the applying frequency. The charging curves of the ten-layer sample using a 2.2 μF capacitor, in normal walking and fast walking modes are compared in Figure 12c. It shows that in fast walking mode, the sample charges the capacitor to 5 V in 2.9 s. Thus its unit energy output by charging the capacitor is 9.5 μJ/s, which is about twice of what it produces in normal walking mode.

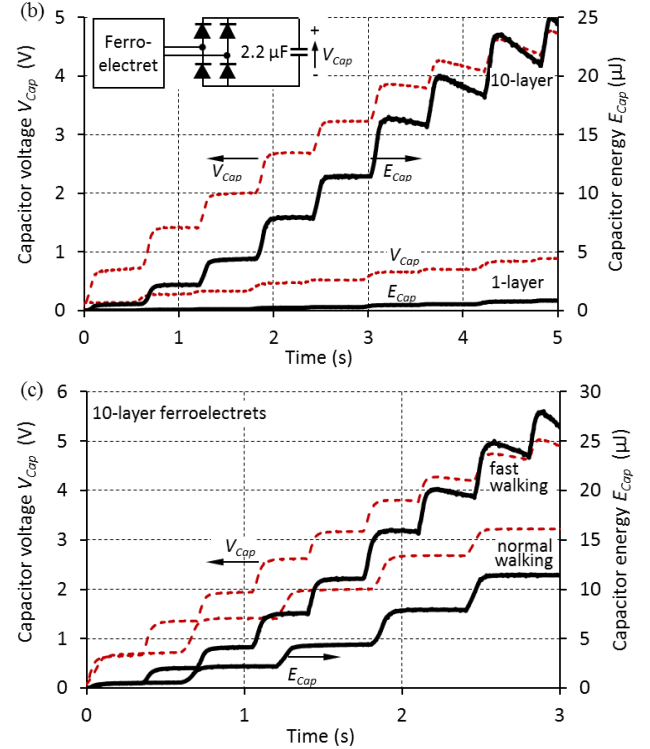
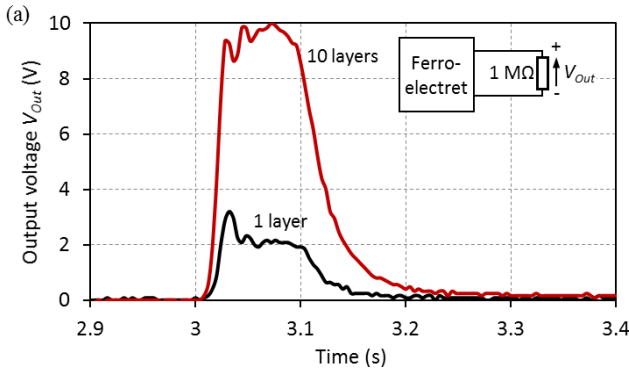


Figure 12. (a) Output voltage pulses of single-layer and ten-layer PP in normal walking mode. (b) Capacitor voltage and energy of single-layer and ten-layer PP. Normal walking mode, and rectification into a 2.2 μF capacitor. (c) Capacitor voltage and energy of ten-layer PP foam under normal and fast walking conditions. Rectification into a 2.2 μF capacitor.

In real applications, the total area of one insole can fit three of these ten-layer samples, each with about 2mm thickness. Therefore, if used the energy output of these ferroelectrets to charge a capacitor installed in an insole, by estimation about 14.6 μJ/s of energy can be produced from a person walking normally, and about 28.5 μJ/s of energy if walk fast. Considering that a typical bluetooth low-energy chipset consumes 30 to 70 μJ of energy per transmission [46-47], depending on the size of the package, these ferroelectrets are potentially capable of powering wireless body-worn sensors for signal transmission in every 2 to 3 s.

4 CONCLUSIONS

The energy harvesting ability of single layer and multilayer ferroelectret PP foams is investigated in this work. An electrodynamic instrument is used to quantify the applied compressive forces and their frequency, thus quantitatively correlates the output energy to the forces by resembling human walking. The results shows that the peak power of a single layer PP foam with electrode size of 50 mm × 60 mm reaches its maximum value with an external resistance load at about 79.2 MΩ in normal walking mode, whilst the maximum output energy occurs at 500 MΩ as the duration of output pulses increases with increasing resistances. However, considering the circuit design in real applications, 1 MΩ of resistance is used for the purpose of directly powering an electronics circuit. By varying the values of the applied compressive forces and

momentums, their effects on the energy output are demonstrated. Three modes of force simulation are designed to resemble the compressive forces applied from human walking. The energy outputs of single-layer PP ferroelectret are characterized using these modes, showing output peak power of 10.2 μW and energy of 1.12 μJ in normal walking mode. The ratios of voltages between the negative pulse and the positive pulse in these modes are also compared.

To further increase the output power, multilayer PP ferroelectret is fabricated in this work. The synchronization in outputs from each layer is studied using simulation and being supported by the experimental results. It demonstrates the importance of bonding between layers in synchronizing the energy outputs. Finally, the energy output of the single-layer and ten-layer PP ferroelectrets are compared by charging a capacitor. The ten-layer ferroelectret shows a significant improvement of energy output comparing to that of single-layer, producing pulse with peak power of 100 μW and energy output of 11.2 μJ , with charging ability 29.1 times better than the single-layer. The ten-layer PP ferroelectret demonstrates energy output that could be capable of powering the start-up and transmission of wearable electronics.

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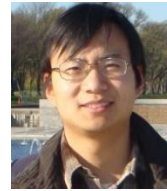
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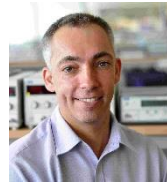
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