Full paper

Performance improvement of flexible piezoelectric energy harvester for irregular human motion with energy extraction enhancement circuit

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A B S T R A C T
Flexible piezoelectric energy harvesters (f-PEHs) have drawn attention for their potential use as power sources for wearable electronics. However, the amount of power harvested from conventional f-PEHs is still insufficient for achieving energy autonomy; hence, they are only used for limited applications. One of the effective approaches to enhancing the energy extraction from an f-PEH is to optimize the harvesting circuits. In this article, an energy extraction enhancement circuit (EEEC) using an f-PEH based on piezoelectric (PZT) material is reported to improve energy harvesting from random energy inputs with varying magnitudes and intervals, just like sporadic and irregular human movement. An f-PEH with a total thickness of 170 µm is utilized, which provides sufficient flexibility for attachment on clothes or human skin. By minimizing the capacitive load experienced by the PZT material during deformation, the EEEC maximizes the output voltage and increases the amount of extracted energy with low static power consumption (1.15 nW). Compared with a conventional full bridge rectifier (FBR)-based harvesting circuit, energy extraction is enhanced up to 495%.

1. Introduction

The advent of the Internet of Things (IoT) has greatly increased the use of wearable electronics in every aspect of daily life, which can provide a variety of information related to personal healthcare [1–9]. For instance, a wristband activity tracker can collect various fitness-related information such as heartbeat rate, sleep quality, walking distance, and estimated calorie consumption [10,11]. To power wearable electronics, commercial rechargeable batteries have been widely utilized, which require periodic recharging due to their limited energy storage capacity. However, repeated battery charging disrupts the continuous monitoring or diagnosis of the owner’s conditions since the wearable devices typically have to be taken off during recharging. To address these issues, wearable electronics have been integrated with energy harvesting technology with the goal of achieving self-powered systems [12–23], where device operation can be sustained with harvested energy.

Among various approaches geared towards creating a self-powered system, flexible piezoelectric energy harvesters (f-PEHs) have attracted considerable attention as potential continuous power sources for wearable electronics [24–26]. f-PEHs have a remarkable capability to generate electricity even from slight mechanical movements common in our environment, such as human activities [27,28], machinery vibrations [29,30], and even wind or ocean waves [31]. Several research teams have reported f-PEHs based on a variety of piezoelectric materials, including ZnO, BaTiO3, and Pb(Zrx,Ti1-x)O3 (PZT) [32–41], but the relatively small amount of energy harvested from these f-PEHs restricts the range of applications. It is thus desirable to design an energy harvesting circuit that enhances the amount of energy extracted by an f-PEH.

Although there have been numerous circuits designed for efficiently harvesting energy from PEHs, most of these earlier works focused on optimizing harvesting circuit operation for cantilever-based structures where output is periodic sinusoidal due to the mechanical resonance...
excited by external vibrations [42,43]. However, this approach is not applicable for f-PEHs combined with wearable electronics since the output generated from human motion is irregular rather than periodic sinusoidal by nature. An f-PEH generates extremely inefficient output power with varying amplitudes at random intervals like human motion. The amplitude of an output pulse is proportional to the amount of deformation applied to the f-PEH, and the interval of the output pulses is determined by the period of the motion. Recently, there was an attempt to implement a PZT energy harvester for pulsed inputs [44], but it could only be used for PZT harvesters with a large capacity since it required a high activation energy.

Herein, we report an energy extraction enhancement circuit (EEEC) with an f-PEH based on PZT material to improve energy harvesting from irregular energy input. A flexible PZT thin film on a plastic substrate was fabricated using inorganic-based laser lift-off (ILLO). The resulting product can be attached to clothes or skin to harvest energy from human motion [45–48]. The EEEC was designed as an inductor-based circuit to minimize energy loss during the current flow from f-PEH to the battery through an inductive converter. To handle the high voltage output (> 140 V) of the f-PEH efficiently, high-voltage-tolerant discrete components are utilized for most of the passive elements, while standard voltage (3.3 V I/O) process is utilized for integrated circuit fabrication for cost-effectiveness. By minimizing the capacitive load seen by PZT material, the EEEC maximizes the output voltage of f-PEH and increases the amount of extracted energy. The minimum activation energy (i.e. harvesting overhead) for the proposed EEEC is 13 nJ per pulse, which is very low compared with previously reported paper of 12 μJ [44]. The energy extraction is enhanced up to 495% compared with conventional full bridge rectifier (FBR). The proposed EEEC also has very low static power consumption (1.15 nW), which is a very important metric for energy-efficient harvesting operation with sporadic energy inputs.

2. Experimental section

2.1. Preparation of a flexible piezoelectric energy harvester

The prepared PZT sol-gel (MEMS Solution, Inc.,) was spin-coated onto a sapphire substrate at 2400 rpm for 30 s. To crystallize spin-coated PZT, heat treatment was conducted using rapid thermal annealing (RTA) at 650 °C for 60 min in air atmosphere. Spin-coating and heat treatment were repeated 20 times to obtain 2-μm thickness. An adhesive epoxy (ultraviolet sensitive polyurethane) was also spin-coated onto thin-film PZT, which was then attached to the flexible polyethylene terephthalate (PET) substrate (4 cm × 4 cm × 125 μm). The ultraviolet- UV)-sensitive epoxy was optically cured by a UV light for 200 s. The ILLO process (XeCl excimer laser, 4.03 eV photon energy) was used to interface the test IC with a PC. Analog and digital test signals obtained from the movement of various parts of the body, such as elbow, ankle, knee, or shoulder joint, have irregular and sporadic characteristics with varying magnitude due to random and intermittent human motion. The piezoelectric energy harvester can be approximately modelled as a current source with instantaneous current (i(t)) and an internal capacitance (C d) in parallel [42]. As the PZT is bent, the generated i(t) charges the internal load C d and potential external load (C load), developing voltage (V c) at the output.

Fig. 1a illustrates the conceptual scheme for energy harvesting from small human movements using an f-PEH attached to a human elbow. The f-PEH was fabricated using a protocol similar to that found in our previous reports, as described in the experimental section [38]. Electrical signals obtained from the movement of various parts of the body were interfaced to a test IC through Analog Discovery 2® oscilloscope to observe the digital signal and input/output voltage waveforms.

2.2. Design and fabrication of the harvesting circuit

The harvesting circuit was designed and simulated in commercial standard voltage CMOS process (180 nm, 3.3 V I/O, 6 metal layers). After functional verification simulations, the harvesting circuit’s layout was designed and sent to an integrated circuits (IC) manufacturing company for fabrication. The fabricated IC was then packaged and wirebonded with a pin-grid-array (PGA) package so that it could be plugged into a socket on a printed circuit board (PCB). The PCB is designed to support an automated test. The energy source (PZT harvester) and all testing equipment are connected through the PCB, and the harvesting circuit operation is controlled for proper measurement. Fig. S1 shows the block diagram of the test set up. Analog Discovery 2® was used to interface the test IC with a PC. Analog and digital test patterns are applied to test IC through Analog Discovery 2® and the test patterns are controlled with the LabVIEW®. The measurements were carried out for different bending speeds and displacements applied on the f-PEH by adjusting bending configurations with bending machine controller.

2.3. Characterization and electrical measurement

The PZT energy harvester was bent by a custom-designed linear stage. A Keithley 2612A sourcemeter was used to measure the open-circuit voltage and short-circuit current from the f-PEH as a result of periodic bending/unbending motions. A Keysight B2912A source measurement unit was used to measure the voltage and current with EEEC operation, and a Tektronix MSO5204B oscilloscope was used to observe the digital signal and input/output voltage waveforms.

3. Result and discussion

The total energy generated by the piezoelectric energy harvester can be calculated by integrating dW for the duration of the bending operation:

$$ W = \int dW = \int_0^Q \frac{q(t)}{C_L} dq = \frac{1}{2} \frac{Q^2}{C_L} $$

From the above equation, the total amount of energy generated by f-PEH is inversely proportional to C L (Fig. 1b-i). This implies that the energy derived from a PZT harvester can be maximized by minimizing C d, i.e., setting explicit C load to 0. Therefore, one of the key approaches of this work is to minimize the load capacitance by removing explicit load capacitance at the harvesting circuit interface and isolating the energy harvester from the rest of the EEEC during deformation.

As the load capacitance is reduced, more energy is extracted and higher voltage is accumulated at the output, as shown in Fig. 1b-ii. Therefore, the harvesting circuit must be designed to handle very high voltages (> 140 V) generated by the f-PEH. The proposed EEEC can deal with high voltages with pulsed input by using high-voltage-
Fig. 1. (a) A schematic illustration of wearable applications using the flexible PZT energy harvester. Load capacitance seen by PZT is minimized by eliminating explicit load capacitance. (b) Driving mechanism of the EEEC. i) Maximum energy is extracted by minimizing load capacitance. ii) A harvesting circuit is required to handle high-voltage pulse inputs. iii) Up to 495% improvement is observed compared with simple rectifying circuit (FBR). (c) Chip micrograph.

Fig. 2. (a) A photograph of the flexible PZT energy harvester bent by tweezer. The inset shows the OM image of the IDEs. (b) XRD pattern of the PZT thin film on a PET substrate. The inset shows a cross-sectional SEM image of the flexible PZT energy harvester. (c) High-resolution TEM image and FFT pattern (inset) of a PZT thin film. (d) An OM image of the transferred PZT thin film showing laser shot traces (top-left), and AFM images of each region with single or multiple laser shots during the ILLO process. (e) The generated output open-circuit voltage and short-circuit current from the f-PEH. (f) The charged voltage in 10 µF, 22 µF, 33 µF, and 68 µF electrolytic capacitors by the flexible PZT harvester. The inset presents a schematic circuit diagram.
tolerant discrete components for most of the passive elements. When the peak voltage is detected at the end of PZT deformation, the EEEC efficiently converts the high output voltage to low voltage to store energy on battery. With such a maximized energy extraction approach, significant improvement in the amount of harvested energy is observed. The amount of energy harvested from a single pulse with the proposed harvesting circuit (EHRV) is improved by up to 495% compared with that obtained with a simple rectifying circuit (E_FBR), as shown in Fig. 1b-iii. The inductor-based harvesting circuit is composed of a control circuit and power switches to control generated charge flow.

Fig. 1b-iii only shows the conceptual explanation of energy extraction enhancement circuit. However, complete measurement details are presented in the later sections. Fig. 1c shows the micrographic image of the EEEC whose integrated circuits for control are fabricated in 0.18-µm standard voltage (3.3 V I/O) process.

Fig. 2a shows that the f-PEH with lateral type IDEs has high flexibility and durability under bending. The open-circuit voltage generated by the f-PEH is proportional to the inter-electrode gap on the PZT materials. Since the interval between the electrodes can be easily adjusted through a photolithography process up to a few hundred micrometers, higher voltage can be obtained from the IDE-based energy harvesters compared to those with a metal-insulator-metal (MIM) structure. As shown in the optical microscopy (OM) image of the f-PEH (inset of Fig. 2a), the IDEs were designed with an electrode width of 100 µm and inter-electrode gap of 100 µm. The square-shaped marks shown in the OM image are the traces of the laser shots produced during the ILLO process.

Fig. 2b presents the X-ray diffraction (XRD) and scanning electron microscopy (SEM) analysis. The XRD pattern was indexed with a reference pattern for tetragonal PZT (ICDD Card No. 33–0784) and rhombohedral PZT (ICDD Card No. 73-2022). The results revealed that the polycrystalline PZT with random orientation was well crystallized into a perovskite structure in which tetragonal and rhombohedral phases coexist. In order to test mechanical property of PZT film, the uniaxial tensile test was conducted. As shown in Fig. S2, PZT film on PET substrate shows ductile fracture with the mechanical strength of 90.4 MPa and the Young’s Modulus of 3.76 GPa. The SEM image (inset of Fig. 2b) shows that the PZT thin film with a thickness of 2 µm was successfully transferred to a PET substrate without mechanical damage such as fracture, cracking, and waviness. A cross-sectional SEM image of the magnified PZT layer (Fig. S3) was also observed to investigate the compactness of PZT thin film, which clearly shows a high compact
structure of the film. Fig. 2c presents the high-resolution transmission electron microscopy (HRTEM) image and the fast-Fourier transformation (inset of Fig. 2c), which show the exact lattice configuration of the perovskite PZT particles. Fig. 54 depicts the P-E (Polarization-electric) hysteresis loops of PZT film with increased applied electric field at a fixed frequency of 100 Hz. The film exhibited symmetric hysteresis loop with remanent polarization (P_r) of 63.7 pC cm^{-2} and coercive field strength (E_c) of 167.3 kV cm^{-1} at maximum electric field of 300 kV cm^{-1}. As shown in Fig. 2d, atomic force microscopy (AFM) images reveal the surface morphology of the PZT thin film transferred onto the PET substrate. The incident beam of the excimer laser is absorbed in the PZT layer while passing through the sapphire mother substrate due to the difference in band gap of each layer during the ILLO process [38]. Thus, the interface between the PZT and the sapphire was locally vaporized, which creates surface fluctuation in the region where a single laser shot is irradiated. In the double and triple shot regions, where the laser track is overlapped, repeated laser shots melt the PET interface, resulting in flattening as the fluctuation decreases. The root mean square (RMS) roughness of single, double and triple laser shot regions is reduced to 23.6 nm, 14.3 nm, and 6.93 nm, respectively.

The electrical output performance of the f-PEH during mechanical deformation is shown in Fig. 2e. It generated an open-circuit voltage of 165 V and a short-circuit current of 1.5 µA as a result of the continual bending/unbending motion induced repeatedly by a linear motor with a curvature of 0.5 cm^{-1}, a strain rate of 2.3% s^{-1}, and a frequency of 0.4 Hz. Fig. 2f presents graphs of charging four different capacitors (with capacitances of 10 µF, 22 µF, 33 µF, and 68 µF) by periodic bending deformation of the f-PEH. The capacitors were charged by the PZT harvesting device from 0 V to 1 V within tens to hundreds seconds (48 s for 10 µF, 86 s for 22 µF, 141 s for 33 µF, and 288 s for 68 µF). An FBR was utilized to rectify the electrical output to charge the capacitors, and the circuit diagram of the rectifier is shown in the inset of the Fig. 2f.

Fig. 5a shows the operation details of the proposed harvesting circuit. An inductor-based energy harvesting circuit is implemented since it can effectively handle varying input voltage with wide continuous range of voltage conversion ratios, whereas capacitor-based circuits only support limited and discrete conversion ratios. The f-PEH is connected to the harvesting circuit through an FBR for rectification. In conventional harvesting circuits, a buffer capacitor (C_BUF) is added at the output of the FBR (V_RECT) to provide temporary energy storage and control impedance. In addition to C_BUF, the parasitic capacitance of the harvesting circuit (C_PAR) is seen as load capacitance for f-PEH during deformation. In the proposed EEEC, C_BUF is removed to minimize the load capacitance. Furthermore, by inserting switch S1 between the FBR and the harvesting circuit and keeping S2 turned off during deformation, C_PAR is isolated from the f-PEH, and hence the load capacitance seen by the f-PEH is minimized. As the PZT is bent, current (I_PZT) generated by the PZT, and internal capacitance C_P is charged, increasing V_RECT output voltage (© in Fig. 3b). As V_RECT exceeds a certain threshold (V_THR), a wake-up trigger circuit (WTC) activates the harvesting circuit with TRIG signal. By setting an appropriate V_THR level, losing energy by activating the EEEC for a small input can be avoided. As the TRIG signal activates the harvesting circuit, the peak voltage detector (PVD) monitors the V_RECT and detects if it reaches its peak, which indicates the end of the deformation process (© in Fig. 3b).

Once the peak is detected, the energy stored in C_P is transferred to an inductor by connecting S1 and S2 (© in Fig. 3b). Meanwhile, the peak detection (PD) signal activates the inductor peak current detector (IPCD). As C_P is discharged, the inductor current reaches its peak when V_L become 0 V, and this condition is detected by the IPCD. Then S1 and S2 are turned off, and S1 and S2 are turned on to transfer the energy from the inductor to the battery (© in Fig. 3b). As the inductor current become 0, a harvesting cycle is completed, and all circuits are turned off except WTC, which is needed to detect the next input.

Fig. 3c shows the measurement results for the generated energy and voltage versus the explicit load capacitance. For these measurements, the load capacitance was connected to the PZT harvester while the EEEC was not connected, and the generated energy values at the end of a single bending/unbending operation of the f-PEH were measured. This graph verifies that the energy generated by a single bending/unbending operation of the PZT harvester decreases as the C_LOAD seen by the energy harvester is increased. The generated peak voltage also decreases as load capacitance is increased, as discussed earlier.

Measurements were performed with the test setup described in the earlier sections. Current flowing from the inductor to the battery is measured to calculate the harvested energy per pulse, which is referred as E_HRV, in this paper. Energy consumed during the EEEC operation is termed as E_LOSS. For comparison with the conventional circuits, a FBR-based harvesting circuit was utilized. In this kind of circuit, only FBR is connected to the PZT to rectify its voltage and output of the FBR is directly fed to a battery. Energy harvested to the battery in this circuit is termed as E_FB. In this paper. Referring to I_BAT and V_BAT shown in the Fig. 3a, E_FB and E_EEC can be defined as

\[ E_{FB} = \int V_{BAT} I_{BAT} dt \]
\[ E_{EEC} = \int V_{BAT} I_{BAT} dt \]

where t_i and t_f stands for the time when the energy transfer to battery started and finished, respectively.

The f-PEH can be attached to any object, such as clothes and textiles, for powering wearable electronics. Therefore, the output of the f-PEH can be random, as shown in Fig. 4a, with varying amplitude and polarity at different instants of time. As highlighted in Fig. 4a, the proposed harvesting circuit is designed not to be activated for small input pulses. This is because the overhead for harvesting circuit activation could be significant and greater than the amount of energy it can harvest from small pulses. In such a scenario, the net harvested energy can be negative, and hence activation is prevented. The measured waveform confirms that the EEEC is only activated when sufficiently large voltage is accumulated at the output (V_PZT), and the harvested energy is transferred to the inductor when V_L > 0 and transferred to the battery when V_L > 0. A bending machine was used to mimic the human motion for bending the f-PEH, and its operation is illustrated in Fig. 4b. The flexible PZT harvester is gradually bent with displacement Δd for a short duration of time Δt. Then, for the performance analysis, the average bending speed S is defined as

\[ S = \frac{\Delta d}{\Delta t} \]

The measurements were carried out for the bending speeds ranging from 0.64 cm/s to 2.6 cm/s due to the limited Δt ranging from 20 ms to 990 ms with the bending machine. However, energy transfer to battery at the end of bending operation, which can be detected by PZT output voltage peak detection with PVD, only takes a few µs to complete. Therefore, theoretically, harvesting with high frequency pulses as short as a few hundreds of µs is possible.

Fig. 4c shows how the amount of harvested energy per pulse varies for different bending speeds (S) and displacements (Δd) applied to the PZT material. The amount of harvested energy (without subtracting E_LOSS) increases in general as bending speed increases, since less charges leak away during bending process. Slight decrease in amount of harvested energy is observed with the highest bending speed set up, since the harvesting circuit was configured for optimized operation with medium bending speed. Harvesting with the highest bending speed could be also improved with adjusting circuit configuration but details are excluded here since the circuit detail is beyond the scope of this paper. Fig. 4d depicts the amount of energy harvested with the proposed harvesting circuit (E_HRV-E_LOSS) and a conventional FBR circuit (E_FB) for different bending displacements. In this figure, the amount of energy consumed for harvesting circuit operation is taken into account;
hence, $E_{HRV-ELOSS}$ refers to the net energy harvested and stored to the battery. Thanks to the maximized energy extraction of the proposed harvesting circuit, $E_{HRV-ELOSS}$ is higher than $E_{FBR}$ for the entire bending displacement range. The amount of energy harvested by the proposed harvesting circuit is increased to 408% on average compared to that obtained using an FBR. Peak efficiency is achieved when the bending speed is 2.6 cm/s and the bending displacement is 2.5 mm while using 3 V battery voltage. While the amount of energy generated by FBR is 0.262 µJ at this point, that of proposed EEEC is 1.3 µJ, which is enhanced to 495%. Such improvement is significant compared with 205% reported in [42], and 269% reported in [43].

4. Conclusion

A new energy-harvesting circuit for an f-PEH is proposed to enable energy harvesting from irregular human motion. Instead of using a conventional impedance-matching approach, energy extraction is significantly enhanced to 408% on average by minimizing the capacitive load seen by f-PEH. The proposed EEEC also maximizes output voltage up to 101 V with extremely low static power consumption (1.15 nW). The f-PEH with total thickness of 170 µm is utilized, which gives enough flexibility for attachment on clothes or human skin. The f-PEH based on PZT material generated an open-circuit voltage of 165 V and a short-circuit current of 1.5 μA through mechanical bending motion on a linear stage. Thanks to the proposed EEEC, this result increases energy extraction up to 495% than that of conventional full bridge rectifier.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.nanoen.2019.01.049.

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