FLEXIBLE PIEZOELECTRIC STRAIN ENERGY HARVESTER RESPONSIVE TO MULTI-DIRECTIONAL INPUT FORCES AND ITS APPLICATION TO SELF-POWERED MOTION SENSOR

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ABSTRACT

A design of flexible piezoelectric strain energy harvester responsive to multi-directional forces from arbitrary human motions was developed by using polydimethylsiloxane (PDMS) and polyvinylidene fluoride (PVDF). Unlike the most of conventional strain energy harvesters designed to be functional only for single directional motion, our suggested design demonstrated the energy harvesting capability for all the input forces applied in multiple different directions. The measured output voltage was 1.75, 1.29, and 0.98 V for the input force of 4 N at 2 Hz applied in the direction of 0°, 45°, and 90°, respectively. The variation of output peak voltage was within 54% of the maximum value for the identical magnitude of forces when the applied direction varies from pure normal direction to pure shear direction. The harvester could keep output voltage in the similar order of magnitude upon diverse directional forces applied. Through the harvester mounted on a curved human body, the motion between body and arm was successfully converted to electricity.

INTRODUCTION

With an increase in the demand of wearable devices, energy harvesters converting ambient energy into electrical energy have attracted significant interests as supplemental power source for mobile electronics [1, 2]. Among the diverse ambient energy, the energy from human body can be constantly generated regardless of surrounding environmental situations [3]. This nature leads to the development of energy harvesters that may convert various human body energy into electricity [4-8]. Particularly on the strain energy harvesting by human motion, flexibility of harvester is highly desirable in order to be conformably mounted on curved surfaces and subsequently for minimal discomfort of users [9, 10]. Many studies about flexible strain energy harvesters with various principles including piezoelectric [6-8], electrostatic [8] and triboelectric conversion [11, 12] have been reported.

Unlike typical machinery or structures, human motion is multi-directional and unpredictable. However, previously reported strain energy harvesters mostly focused on a single-directional human motion such as bending or contacting of body parts [13-15], which limits effective generation of electrical energy from human motion in arbitrary direction. Thus it is highly required to harvest energy from multi-directional input forces to improve the efficiency of energy harvester.

In this work, a design of flexible piezoelectric strain energy harvester to facilitate the use of multi-directional input force is proposed. The structure of harvester including polydimethylsiloxane (PDMS) bump, frame and slits in the piezoelectric polyvinylidene fluoride (PVDF) film allows effective conversion of strain energy by multi-directional input forces. The fabricated harvester generates output peak voltage about 1.75, 1.29, and 0.98 V for the input force of 4 N at 2 Hz applied in the direction of 0°, 45°, and 90°, respectively. The harvester mounted on a curved human body successfully converted human motion into electrical energy, showing applicability of the developed harvester as a self-powered motion sensor

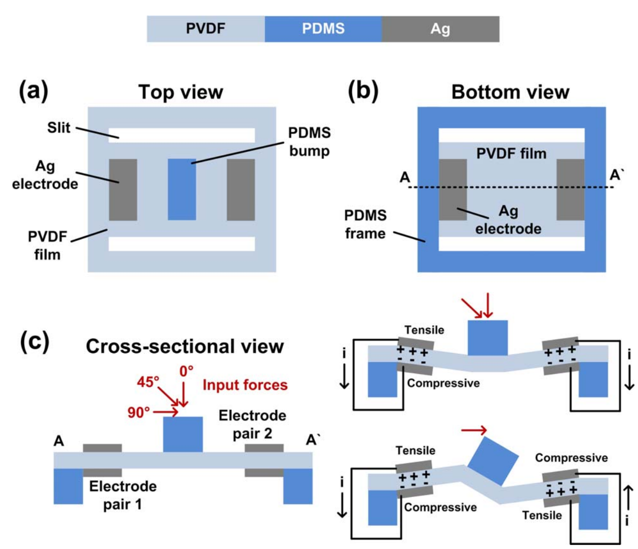

Figure 1: Schematics and working principle of the proposed flexible strain energy harvester. (a) Top view. (b) Bottom view. (c) Cross-sectional view (along the line of A-A` in (b)) of the harvester with energy conversion principle upon multi-directional forces.

DESIGN AND FABRICATION

Figure 1 shows schematics and working principle of the proposed flexible strain energy harvester. We devised a polydimethylsiloxane (PDMS) bump (size: 3×10 mm^2, and thickness: 3 mm) for effective conversion of input forces in arbitrary direction to electrical energy. A PDMS frame (thickness: 3 mm) provides a mechanical flexibility of the harvester and slits (size: 1×15 mm^2) in 110 µm-thick polyvinylidene fluoride (PVDF) enhances the deformation of PVDF film for larger electrical output by lowering the stiffness of PVDF structure. Ag electrodes were defined on both sides of PVDF film. The size of single harvester cell was 25×26 mm^2. For the forces applied to the bump, strain gradient is generated in PVDF film inducing potential difference between top and bottom electrode pair 1 and 2 (Figure 1(c)). For the input force angle of 0° and 45°, the generated current flows from top to bottom electrode on both electrode pairs (identical polarity), while the direction of current flow is reversed for the force in 90° on electrode pair 2 by rotation of the bump structure (opposite polarity).

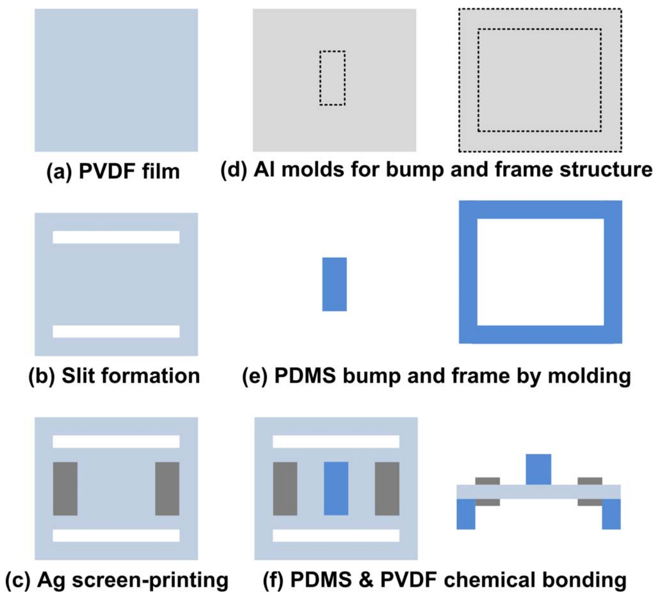

Figure 2: Fabrication process of the proposed harvester. (a,b) Formation of slits by cutting. (c) Screen-printing of Ag to define electrodes. (d,e) Molding of PDMS bump and frame structures. (f) Bonding between PDMS and PVDF.

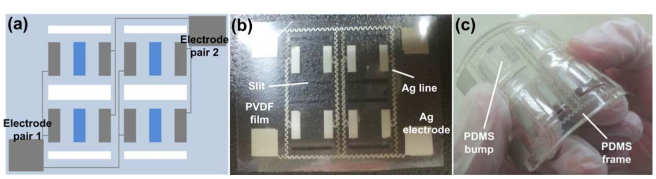

Figure 3: (a) Layout of the harvester array. (b) Photograph of screen-printed Ag electrical paths and electrodes. (c) The fabricated flexible energy harvester array.

In figure 2, fabrication process of the proposed harvester is depicted. Ag electrodes and electrical paths were screen-printed after a commercially available PVDF film was cut for the formation of slits (Figure 2(a-c)). Then the PDMS bump and frame prepared by molding process using Al molds were chemically bonded to PVDF film by 3-aminopropyltriethoxysilane (3-APTES) [16] as shown in figure 2(d-f). The fabricated harvester composed of 2×2 array of the harvester cells (size: 6.5×5 cm^2) and applicable to large area is shown in figure 3. The electrodes shown in figure 3(a) were designed to superpose the power from each harvester cell of an array by sharing the electrical paths. The flexibility of the fabricated energy harvester array is presented in figure 3(c).

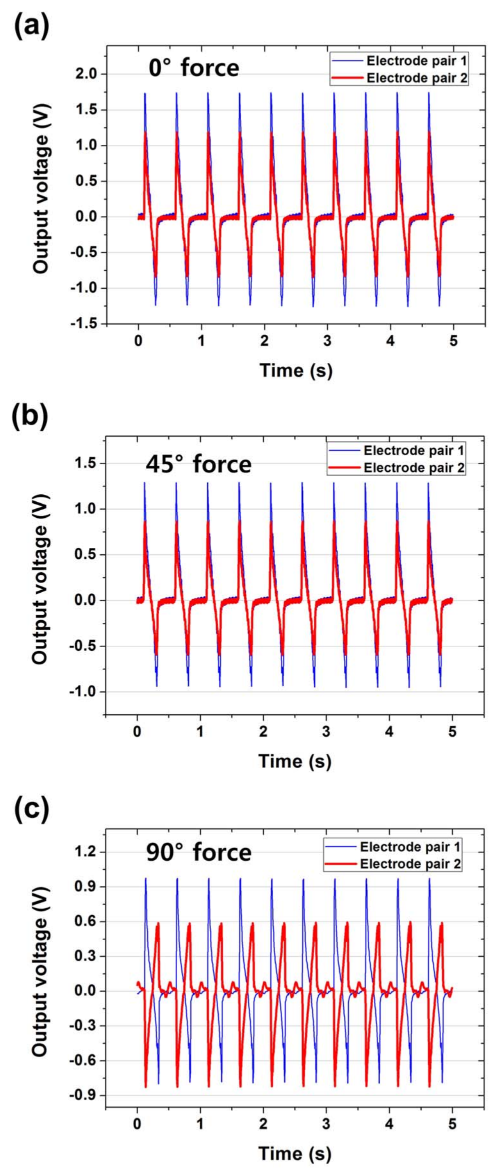

Figure 4: Output voltage of the harvester upon the diverse directions of input force (4 N, 2 Hz). Output voltage by (a) 0°, (b) 45°, and (c) 90° force. The output voltages can be maintained in similar order under various angles of input forces.

RESULTS AND DISCUSSION

The output voltage of the harvester was measured upon the input forces of 4 N at 2 Hz applied on the harvester array in three different directions of 0°, 45°, and 90° as presented in figure 4. The measured maximum output peak voltage was

1.75, 1.29, and 0.98 V for the force angles of 0°, 45°, and 90°. The magnitude of peak voltage by 0° input is the highest and the direction of output current is same between electrode pair 1 and 2 (identical polarity). The magnitude of output peak voltage by 45° input is slightly lower than that by 0° input, owing to the decreased vertical component of input force. The polarity of output voltage by 45° input is identical to the that of 0° input, unlike the 90° input case. For the input force angle of 90°, the strain gradient in PVDF film is reversed on electrode pair 2 and therefore the opposite polarity of output voltage is generated. It is noted that the induced strain is extremely small for the harvester without bump structure when the input force angle is 90° (verified by finite element analysis), implying the output voltage is hardly generated. On the other hand, our design with PDMS bump induces sufficiently large strain on the PVDF film for the shear forces. Through the effective conversion of multi-directional forces enabled by bump structures and slits, the output voltages from the harvester remains in the similar order of magnitude regardless of the angles of input force, demonstrating the ability to harvest arbitrary directional input forces.

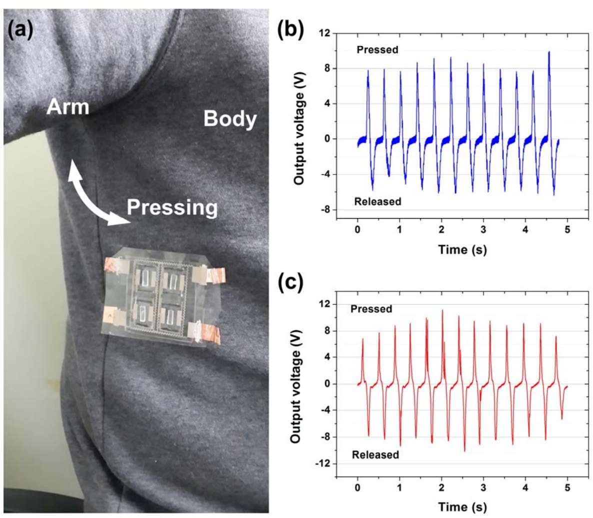

Figure 5: Output voltage from electrode pair 1 and 2 by pressing motion between arm and body. (a) Photograph of the mounted harvester on the human body. (b) Output voltage from electrode pair 1, and (c) Output voltage from electrode pair 2.

To investigate the potential of our harvester for the conversion of real human motion, we mounted the harvester on human body as shown in figure 5(a). By the pressing motion between arm and body, the normal force was applied to the harvester. Figure 5(b) and (c) show the output voltage from electrode pair 1 and 2. The polarity of peak voltages generated on electrode pair 1 and 2 was identical and peak voltages (~10 V) with similar magnitude on electrode pair 1 and 2 were observed. The proposed device could not only harvest electrical energy from human motion, but also tell the motion property. The information of electrical output signal from the harvester, such as magnitude, polarity and frequency, can be utilized to identify the severeness, direction and number count of human movement. Experimental characterization as well as the measurement on human body showed that our harvester facilitates the conversion of multi-directional strain energy from random human motion. An alternative application as a self-powered human motion sensor to monitor the activity of human movement without an external power source [17] was also successfully demonstrated.

CONCLUSIONS

We developed flexible piezoelectric energy harvester responsive to multi-directional input forces. Based on the structural design using PDMS bump, frame and PVDF film with slits, the flexible harvester showed the effective conversion of various directional input forces into electrical energy. The measured range of maximum peak voltages from the fabricated harvester for various input force angles was 0.8-1.75 V. The harvester could maintain output voltage in similar order regardless of the directions of the forces applied. Moreover, the harvester mounted on the human body successfully generated electrical output by the pressing motion between arm and body. The usage as a self-powered human motion sensor was also experimentally demonstrated.

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