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Flexible Energy Harvester with Piezoelectric and Thermoelectric Hybrid Mechanisms for Sustainable Harvesting

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Abstract
In this paper, we present a flexible hybrid energy harvester for single- or multi-source energy collection. To increase harvesting power, piezoelectric and thermoelectric conversions are used simultaneously. The piezoelectric portion of the harvester collects energy from low-frequency kinetic motion using frequency up-conversion. The thermoelectric part is suitable for harvesting energy from a curved surface, thanks to its flexibility. By harvesting from two different energy sources (kinetic and thermal), the harvester allows for sustainable energy harvesting. The average power density obtained was 28.57 and 0.64 $\mu W/cm^2$ by piezoelectric and thermoelectric conversion, respectively.

Keywords Energy harvester · Flexible harvester · Hybrid · Piezoelectric · Thermoelectric

1 Introduction

The use of mobile and wearable electronics has rapidly increased. These devices are typically powered by batteries, and a lot of effort has been put into extending the available lifespan of their power supplies. As a part of the efforts, extensive research has been conducted towards harvesting energy from ambient sources as a sustainable auxiliary power supply [1, 2]. Despite continuing efforts, the output power of these harvesters still needs improvement if they are going to be applied commercially. In addition to the output

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power of the harvester, sustainable energy harvesting is also important for reliable power supply to the electronics.

To increase the harvesting energy, an effective design method is to compose a hybrid type of harvesters on a single device, which harvests energy from single or multiple ambient energy sources using a combination of different energy conversion mechanisms. These mechanisms have included piezoelectric [3–5], thermoelectric [6–9], electrostatic [10], and triboelectric [11] energy transforming phenomena. Hybrid harvesters may collect energy from a single source, increasing the output power per unit area. Hybrid energy harvesters that use multiple conversion mechanisms (such as piezoelectric–electrostatic, or piezoelectric–triboelectric combination) from a single input energy source (mechanical energy) have been researched [12, 13]. While they could effectively improve output power, no energy could be harvested at all when the single energy source disappeared. Some research has also been conducted for the harvest of energy from two or more different sources, using a variety of conversion methods with different types of energy sources [14, 15]. A typical example is a kind of harvesters combining solar and mechanical energies [16]. These harvesters could increase output power extracted concurrently with two types of energy sources. Moreover, they overcome the limitations of a daylight-only solar cell and of originating from weather or location. Harvesting energy from multiple

sources makes it possible to collect energy without depending on a specific type of energy source.

An example of such multiple-energy sources is the human body, which constantly burns calories and generates heat. Human energy has attracted much attention, due to its sustained energy supply and its direct contact with mobile electronics. Harvesting multiple forms of energy directly from the body enables a continuous power supply [17, 18]. However, to be applicable to the human body, the harvester should be flexible or tiny for the convenience of the wearer [19]. Also, since human motion occurs in the low range of frequency, the harvester should be able to take advantage of these low-frequency movements. Various studies for harvesting energy from human motion and body heat have been conducted. These results focused predominantly on the integration of a single energy conversion mechanism on a flexible substrate or on the miniaturization of the devices for user convenience. Since human motion occurs at such low frequencies, research has also been focused on harvesting energy from such low-frequency inputs. Most of these harvesters depend on a single energy source, and research regarding hybrid harvesters for the human body is still insufficient.

In this paper, a flexible hybrid energy harvester is proposed to harness energy from the human body. We can use piezoelectric and thermoelectric conversion mechanisms in combination to enhance energy harvesting and collect it from one of the sources in the absence of the other. The proposed hybrid harvester was fabricated by combining the thermoelectric harvester with our previous work, the piezoelectric harvester [20], without increasing the harvester volume. The piezoelectric conversion can harvest energy from the low-frequency motion, using a frequency up-conversion mechanism. The thermoelectric portion is suitable for harvesting body heat in close contact with the skin, owing to the flexibility of the harvester as a whole.

2 Design and Working Principle

Figure 1a shows the schematics for the hybrid energy harvester. Two piezoelectric cantilevers and a fabric-based thermoelectric harvester are combined on a flexible substrate. The piezoelectric cantilever is positioned such that the thermoelectric harvester is in close contact with the heat source, and is also exposed directly to the air. The schematic of both the piezoelectric and thermoelectric harvesters is shown in Fig. 1b, c. The piezoelectric harvester is composed of two piezoelectric cantilevers with two permanent magnets. For flexibility, the piezoelectric cantilevers are made using flexible polyvinylidene fluoride (PVDF) and polyvinyl chloride (PVC) films.
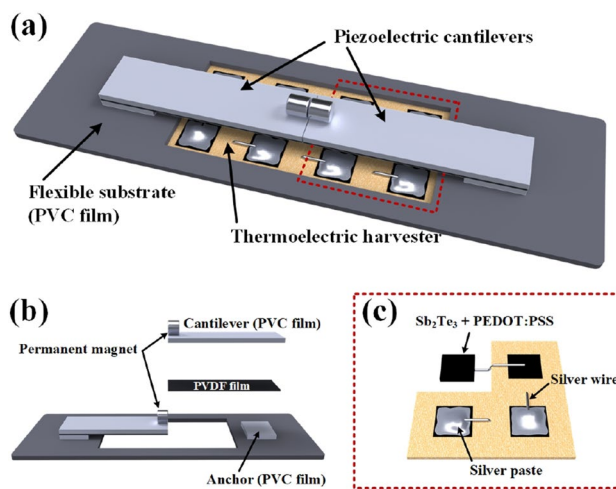

Fig. 1 a Schematic of the harvester: piezoelectric cantilevers and a fabric-based thermoelectric harvester are combined on a flexible substrate. **b** The piezoelectric part is composed of two piezoelectric cantilevers and two permanent magnets. **c** The thermoelectric harvester consists of eight p-type thermoelectric material columns fixed through a flexible fabric substrate

The cantilevers are anchored to the substrate with a PVC anchor, while the other ends are bound to each other by magnetic attraction (Fig. 1b). The thermoelectric harvester consists of eight p-type thermoelectric columns, printed through a gauze fabric substrate. To connect the p-type material in series, the columns were connected using flexible silver wires (Fig. 1c).

The working principle of the piezoelectric and the thermoelectric harvesters is depicted in Fig. 2a, b. The piezoelectric part uses frequency up-conversion to operate in the low-frequency input range. When an external bending load is applied to the harvester, the two cantilevers are deformed together by the magnetic attraction of the permanent magnets. When the restoring force of the bent cantilever becomes larger than that of the magnetic force, the two cantilevers are separated from each other and rapidly vibrate at their natural frequencies.

Figure 2b shows the electrical current direction when a temperature differential occurs at the thermoelectric harvester. For the convenience of fabrication, the thermoelectric harvester was fabricated using only p-type of the thermoelectric material. While traditional TEGs utilize a set of complementary n-type and p-type thermoelectric materials, a single-element device can also be fabricated [21]. Since the thermoelectric harvester is made using only p-type thermoelectric material, the direction of the current is the same when the temperature difference is generated. Eight thermoelectric columns are connected in series through the silver wire spanning from the top of one column to the bottom

Fig. 2 Working principle of the harvester. **a** When external bending is applied to the substrate, the cantilever is released from the substrate and oscillates at its resonant frequency. **b** The current direction when a temperature difference occurs within the thermoelectric harvester
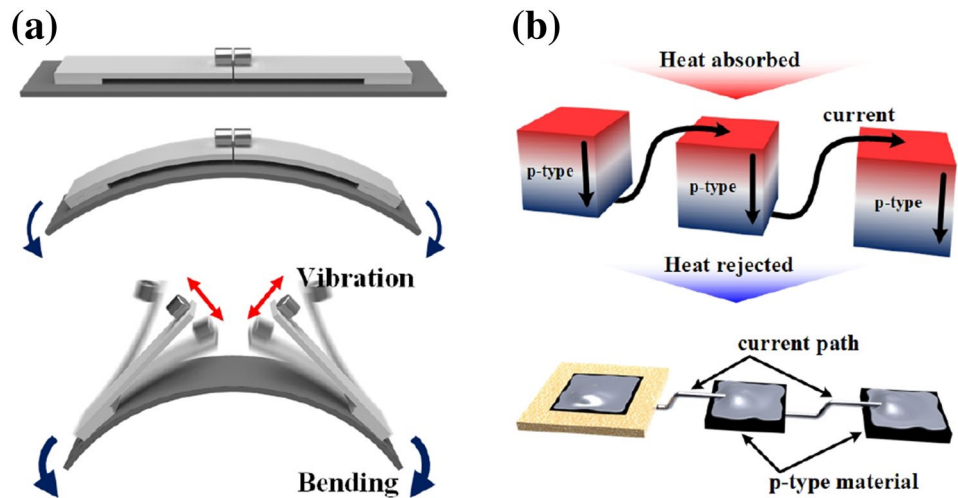
Fig. 3 Fabrication process of the fabric-based thermoelectric harvester. **a** The prepared paste (Sb_2Te_3 + PEDOT:PSS) was screen-printed through the gauze fabric. **b** PDMS was screen-printed onto the areas excluding thermoelectric material. **c**, **d** Silver wire was sewn and silver paste was printed to form an electrical connection between the thermoelectric material columns
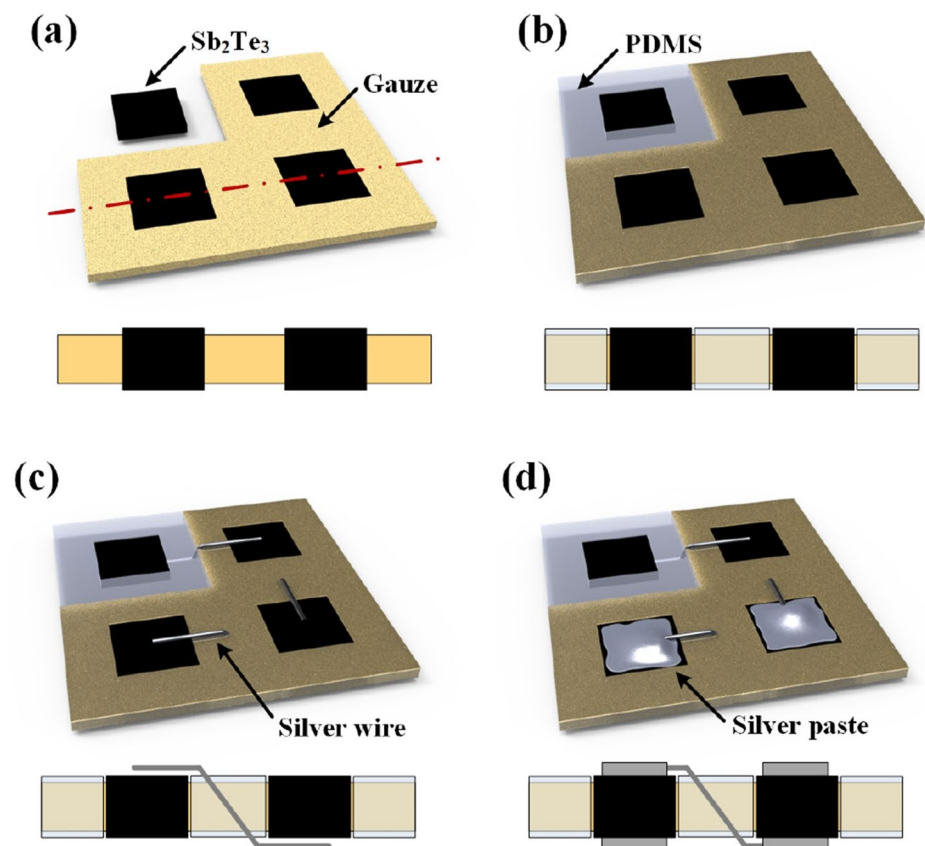
of the next column so that the output voltage between the thermoelectric columns is not canceled.

3 Fabrication

The hybrid harvester was fabricated by combining the piezo-electric and thermoelectric portions after they were prepared separately. Figure 3 shows the fabrication process for the thermoelectric part. First, 10 g of the thermoelectric material Sb_2Te_3 (in powder form) and 5 mL of the conductive polymer poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS) were mixed to a paste for a screen-printing process. The prepared paste was screen-printed through a gauze fabric, to form 500-µm-thick thermoelectric columns, and then cured at 130 °C on a hot plate (Fig. 3a). The dimensions of the thermoelectric columns were 5×5 mm², and 2×4 column arrays were printed in total. After that, the
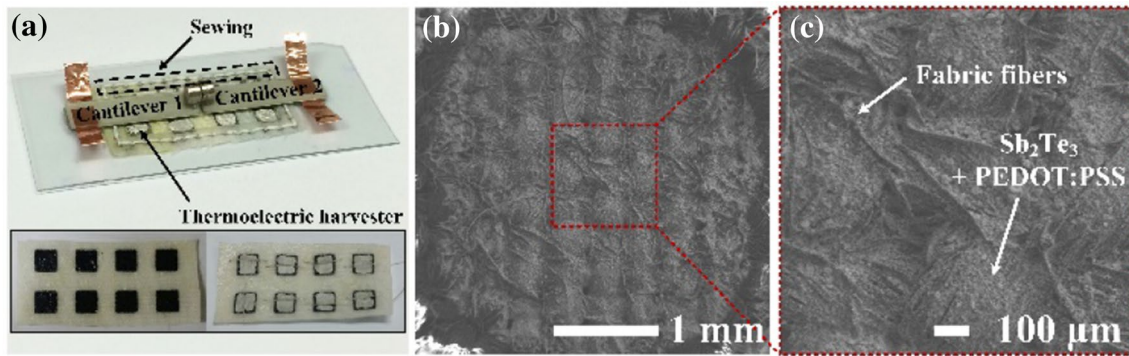
Fig. 4 a Photograph of the fabricated hybrid energy harvester. Inset shows the fabric-based thermoelectric harvester before and after the wiring of the thermoelectric material columns. **b, c** Low- and high-magnification SEM images of the thermoelectric materials printed on the gauze fabric. The thermoelectric materials were evenly printed onto, and through, the fabric

polydimethylsiloxane (PDMS) was screen-printed onto the area surrounding (but not including) where the thermoelectric material was printed (Fig. 3b). The printed PDMS serves to prevent excessive force from being applied to the thermoelectric material when the harvester is deformed. Finally, a silver wire is sewn and the silver paste printed to form an electrical connection between the thermoelectric columns (Fig. 3c, d). Using a typical metal paste as an electrode may cause cracks when the harvester is deformed, which can break the electrical connection. Silver wires allow stable connections to be formed without concern of breakage. Silver wire is also suitable for making fabric-based harvesters and is useful for fabricating electrodes that penetrate the fabric.

The piezoelectric harvester was mainly made of flexible polymer films. First, a flexible PVC film substrate was prepared with the middle part removed, which allows it to be combined with the thermoelectric part. Two 8×8 mm^2 PVC film anchors were bonded to the substrate and two piezoelectric cantilevers were attached to them. The piezoelectric cantilevers were prepared by bonding commercially available PVDF film (P/N: 3-1004346-0, TE connectivity Ltd.) and PVC film; the thickness of each film being 110 µm and 800 µm, respectively. The piezoelectric coefficient of the PVDF is 23 pC/N. The length and width of the cantilevers were 30 mm and 8 mm, respectively.

Individually fabricated piezoelectric and thermoelectric parts were sewn together. Figure 4a shows photographs of the fabricated harvester with the inset showing the thermoelectric harvester before and after wiring of the thermoelectric columns. Figure 4b, c show the low- and high-magnification SEM images of the thermoelectric materials printed on the fabric. The thermoelectric materials were evenly printed onto and through the fabric.
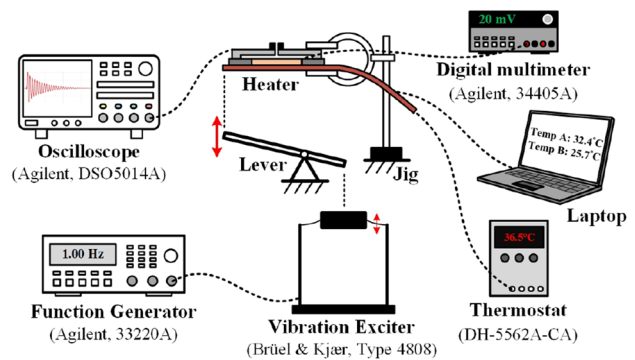

Fig. 5 Experimental setup for testing the hybrid energy harvester. The output characteristics were measured under different thermal and kinetic conditions, as generated by heating tape and a shaker

4 Results

Figure 5 shows the experimental setup for measuring the output characteristics of the fabricated harvester. The output characteristics were measured under different thermal and kinetic conditions generated by heating tape and a mechanical shaker. The vibration of the shaker was transferred through the lever to the harvester, which resulted in bending of harvester. A temperature regulator attached to the heating tape generated thermal input to thermoelectric device.

The output voltage generated by the piezoelectric part is shown in Fig. 6a. When the harvester was bent, the two cantilevers generated voltage with measured peaks of 321 V and 311 V, respectively. To find the maximum RMS power density for the device, the RMS voltage was measured at variable load resistance (Fig. 6b). The RMS power generated from a single cantilever was 68.56 µW with a 5 MΩ load resistance at bending of 0.5 Hz excitation. The power density was calculated at 28.57 µW/cm^2 in the area of a single cantilever 2.4 cm^2. The output power of the piezoelectric
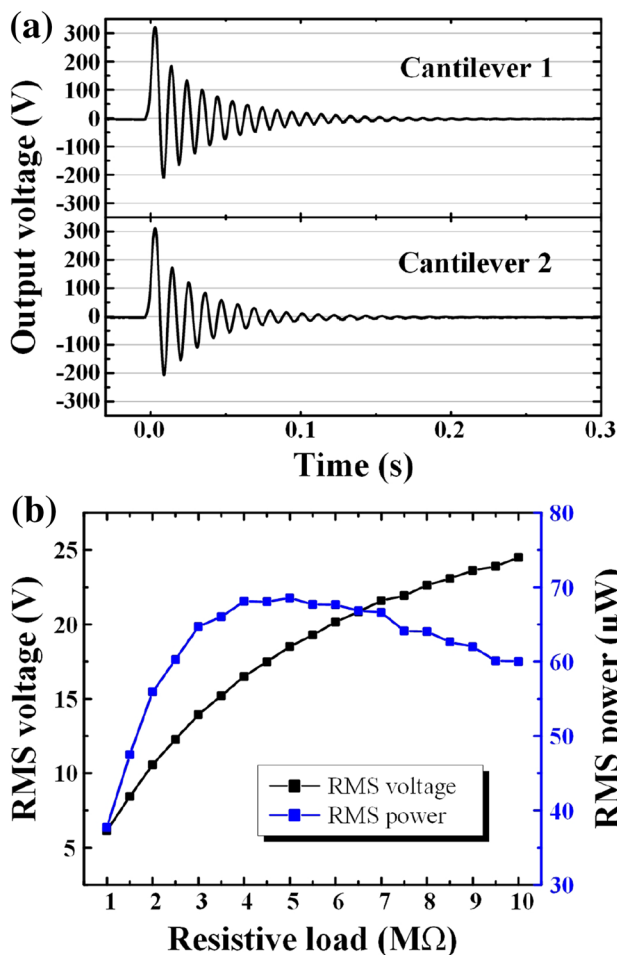
(a)

(b)

Fig. 6 **a** Output voltage generated by the piezoelectric part of the harvester. When the harvester is bent, each of the two cantilevers generates voltage, and the measured peak voltages are 321 V and 311 V, respectively. **b** The RMS voltage and power generated from single cantilevers with variable load resistances

Fig. 7 Thermoelectric output voltage with an increasing temperature difference. Power density generated by the thermoelectric part. At a temperature difference of 9.2 K, the power density was 0.64 μW/cm^2

part could be controlled by adjusting the magnetic force and mass of the cantilever (Figure S1).

We measured the thermal characteristics of a single thermoelectric column before measuring the thermal performance of the entire elements. The temperature difference and the output voltage produced by the single column were measured without bending the element (Figure S2). A temperature difference of 10.1° and an output voltage of 1.75 mV were observed when the heat was applied for 80 s (Figure S2a). In this experiment, the temperature measured through the thermocouples can be found in Figure S2b. Figure S2c shows the Seebeck coefficient of the fabricated thermoelectric column.

After measuring the thermal characteristics of the single column, we experimented with the entire 8 thermoelectric columns. The output voltage and generated power by the thermoelectric part are shown in Fig. 7. Since the device is
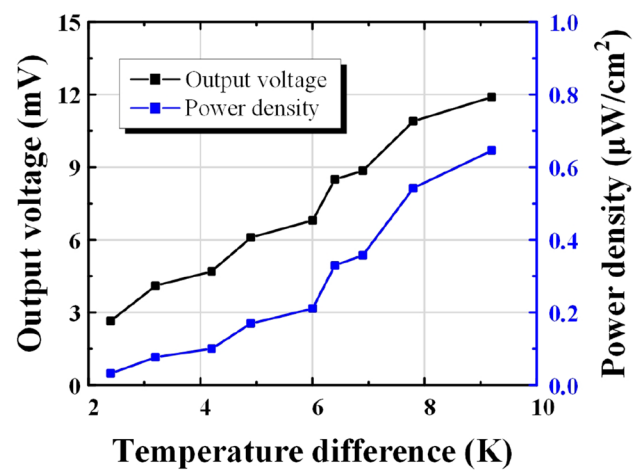
for human application, measurements were performed with a maximum of a 10 K temperature difference. At a 9.2 K temperature difference, the measured output voltage was 11.9 mV. The total electrical resistance of the fabricated thermoelectric part was 27.4 Ω, so the power density generated by the thermoelectric harvesting was calculated as 0.64 μW/cm^2 at a 9.2 K temperature difference. The actual temperature of the cold side was 342.2 K when the temperature difference reached 9.2 K (Figure S3).

To verify the durability of the fabricated harvester, the changes of the output voltage from the piezoelectric part and the resistance of the thermoelectric part were measured by repeating the tests of bending motions. When the harvester was bent repeatedly (with a radius of curvature of 3 cm), it endured over 1200 cycles without notable changes to the output voltage (Fig. 8a). When bent with less than a 1.5 cm radius, cracks formed in the thermoelectric material and the resistance increased rapidly. However, there was no resistance change to the deformation of the radius of curvature that operated the piezoelectric part, and this resistance was kept at a constant value even in repetitive operation (Fig. 8b).

5 Conclusion

In this work, a piezoelectric-thermoelectric hybrid energy harvester was developed using flexible materials. The piezoelectric part of the harvester can harvest energy from low-frequency motion, using frequency up-conversion. The thermoelectric part is suitable for harvesting from a curved surface, owing to the flexibility of the device. The fabricated harvester can collect energy from two different types of sources: thermal and kinetic. By harvesting from two
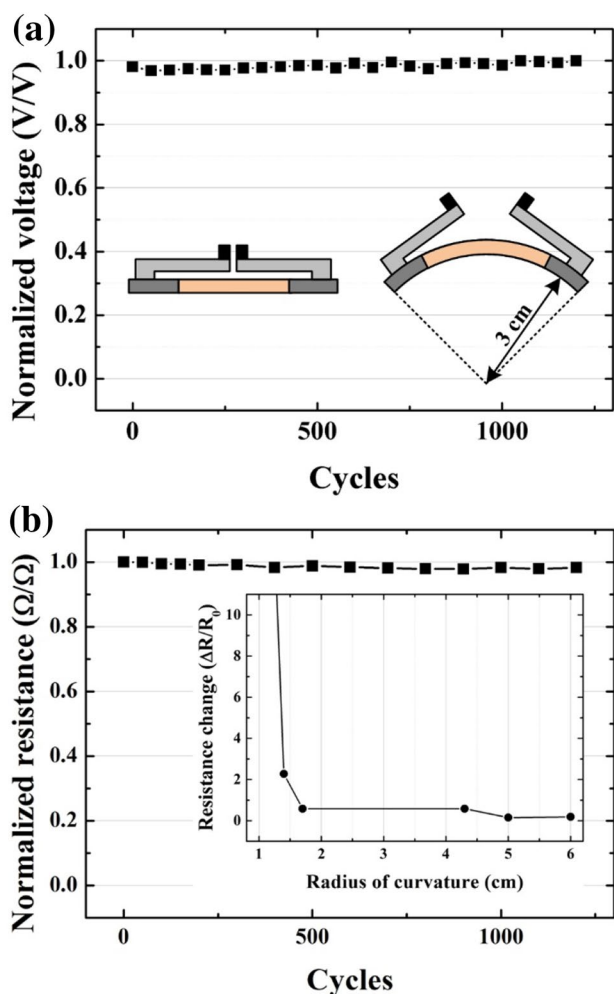
Fig. 8 The output voltage from the piezoelectric part. The resistance of the thermoelectric part was monitored during repeated cycles of bending. **a** The piezoelectric part of the harvester endured over 1200 cycles without notable changes to the output voltage. **b** There was no resistance change in the deformation of the radius of curvature that operated the piezoelectric part, and resistance maintained a constant value—even during repetitive operation

different sources at the same time, the total harvested energy is increased. Even when one of the energy sources is not present, harvesting energy from other source continues and it allows for an uninterrupted energy collection. The maximum RMS power density of the piezoelectric part was 28.57 µW/cm^2, and that of the thermoelectric part was 0.64 µW/cm^2 at a 9.2 K temperature difference. The output power of the thermoelectric part is lower than that of the piezoelectric part, but it can generate energy continuously to maintain a stable energy supply. In addition, it is expected that the thermoelectric harvester performance can be improved when the n-type and p-type thermoelectric materials are used simultaneously. Because it is fabricated by using a screen printing process, the output power of the thermoelectric harvester can be further improved when fabricated in large arrays.

Considering its flexibility and ability to harvest mechanical inputs at low frequencies, intimate attachment to the joint such as knees and elbows would be one possible ideal use of the proposed hybrid harvester. To be closely attached to the joint for practical application, the harvester may need to be smaller in size or additional substrate such as a bandage should be used.

Compliance with Ethical Standards

Conflict of Interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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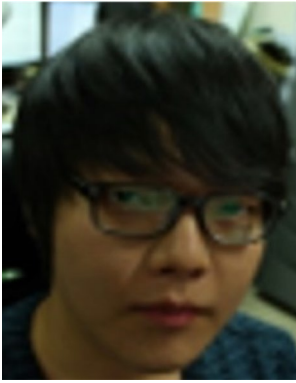
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