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Wearable thermoelectric generator to harvest body heat for powering a miniaturized accelerometer

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HIGHLIGHTS

- A novel structural design of the wearable TEG to harvest body heat is developed.
- The TEG features excellent flexibility and high power generation for body heat harvesting.
- A miniaturized accelerometer is powered by the TEG to detect body motion through harvesting wrist heat.

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ABSTRACT

Wearable thermoelectric generators (TEGs) enable the conversion of human body heat into microwatts to milliwatt electricity, which can be utilized to power miniaturized electronic devices for motion detection and healthcare monitoring. This paper presents a novel wearable TEG with 52 pairs of cubic-shaped thermoelectric legs to harvest human body heat. The thermoelectric legs are made of P-type and N-type Bi_2Te_3-based powder materials, and are connected electrically in series through soldering. The flexible printed circuit board (FPCB) with special holes is designed and used as substrate to enhance the flexibility of the TEG for wearable applications. The performances of the TEG, including the bulk thermoelectric legs, are characterized. The results show that the TEG can generate an open-circuit voltage of 37.2 mV at $\Delta T = 50$ K, and the internal resistance of the TEG is quite low at a value of 1.8 Ω. Then the TEG was worn on a human wrist to harvest body heat and power a 3-axis miniaturized accelerometer for detection of body motion at $\Delta T = 18$ K. The results demonstrate that the developed wearable TEG features high output performance and could be utilized for powering electronics and/or sensors by harvesting human body heat.

1. Introduction

Wearable electronics and sensors are now widely utilized for health monitoring [1], Internet of Things (IoT) [2], and motion detection [3], etc. However, their limited energy storage and the periodic changes required for additional power supply modules, such as lithium cell and nickel-zinc batteries, limit the application of these electronics and sensors [4]. Therefore, the demand for sustainable power supplies for these devices is urgent, and energy-harvesting modules represent a promising method to achieve self-powered electronic systems. Thermoelectric generators (TEGs) can convert harvested heat into electricity based on the Seebeck effect [5]. Thus, the human body can be seen as a stable and sustained natural heat energy source [6]. To this end, many researchers have been attracted to the development of wearable TEG devices to harvest human body heat for powering electronics.

The structural design of a wearable TEG is crucial because it has a significant effect on the performance of the device. For wearable applications, the TEG needs to have sufficient flexibility, and in-plane [7,8] and cross-plane [9,10] structural designs are commonly utilized for this reason. For TEGs with an in-plane structure, the rigid thermoelectric legs are arranged parallel to the substrate, as those in thin-film TEGs. Rojas et al. [7] demonstrated an affordable and flexible TEG, which deposited the thermoelectric materials on paper substrates by PVD magnetron sputtering. Madan et al. [8] proposed a TEG prototype, which has 50 thermoelectric legs printed on a polyimide (PI) substrate. Because the in-plane TEG has a small thickness, the temperature difference in the device is also low. Thus, the induced power and power density are relatively low, which limit applications of this type of TEG. As for cross-plane structures, Kim et al. [9] developed a flexible and lightweight wearable TEG based on glass fabric for harvesting human

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body energy. The results showed that this TEG design could be bent into a curved surface with a radius of curvature less than 2.0 mm. In comparing these two types of structural designs, the in-plane TEGs usually have greater internal resistance, which will lower the voltage and power generation. The cross-plane TEG has a larger contact area for the thermoelectric legs and electrodes, so most of the heat will flow through the thermoelectric legs and in turn generate high voltage and power. In this study, the cross-plane structure is selected to design a novel wearable TEG with the aim of enhancing the performance for body heat harvesting.

The fabrication methods and procedures for generating a wearable TEG are critical and need to be explored. For cross-plane TEGs, thermoelectric legs can be printed [11,12], electrochemically deposited [13], and soldered [14,15] onto a flexible substrate. Using a printing process, the bendable conductive polymer [11] and powder mixture [12] have been used to fabricate a TEG. Due to the low electrical conductivity of the polymer and powder mixture, the figure of merit (*ZT*) values for these TEGs are also low and then the generated voltage and power will not be high enough for powering a micro-sensor. By using an electrochemical deposition method, Glatz et al. [13] presented a prototype for a miniaturized TEG. This process is too complex and the cost may be too high. Recently, the soldering method has been utilized to solder bulk thermoelectric legs onto a flexible printed circuit board (FPCB) [14,15]. The generated TEGs usually have greater strength and stability, and high performance of the TEG can be expected. As for the soldering process, the selection of the soldering material and fabrication procedures may have a substantial effect on the performance of the TEG. Mismatches in the solder selected, thermoelectric legs, and electrodes will introduce high thermal and electrical contact resistances at the interface layers. Therefore, the selection of the soldering material and soldering procedure to develop a wearable TEG need to be investigated and is one goal of this research.

Using various TEG designs, wireless transceivers [16], electrochromic glucose sensors [17], and biomedical hearing prostheses [18] have been successfully powered for health monitoring. Among wearable electronics, miniaturized accelerometers can be used to detect body motion and they play an important role in clinical [19] and biomedical [3,20] applications. To power a miniaturized accelerometer, the required power consumption is quite low, at milliwatt level. Using our developed wearable TEG to harvest body heat, a miniaturized accelerometer can be self-powered for actual motion detection. The remainder of this paper covers the following:

- A novel wearable TEG to harvest body heat to power miniaturized electronics was developed. The FPCB with special holes that is used as the substrate can enhance the flexibility of the TEG for wearable applications. The selection of soldering material on the cold side and the hot side of the TEG and the proposed fabrication procedure can reduce the contact resistance at the interface layer.
- The performance of the TEG is experimentally characterized. The internal resistance, voltage and power generation are studied.
- An experiment with a human wearing the TEG on the wrist and powering a miniaturized accelerometer for body motion detection is carried out. Under different body motion conditions, three-axis acceleration values are successfully recorded.

2. Wearable TEG

The schematic view of the wearable TEG on a human wrist to harvest body heat and power a miniaturized sensor is illustrated in Fig. 1(a). A step-up circuit is utilized to connect the wearable TEG and the sensor. The human body is a great thermal source, which constantly spreads heat into the ambient air, and this makes the skin on the wrist have a relatively constant temperature of 36.5 °C [21]. Therefore, the bottom surface of the TEG in contact with the skin is regarded as the hot side. The top surface of the TEG is exposed to ambient air and is the cold side. Then the temperature difference between the hot and cold sides of the TEG will lead to a steady-state heat flux flowing through the TEG. Based on the Seebeck effect, this temperature difference can be converted into electrical voltage, which is then boosted by a DC-DC step-up converter and it is used as the power input of the miniaturized sensor.

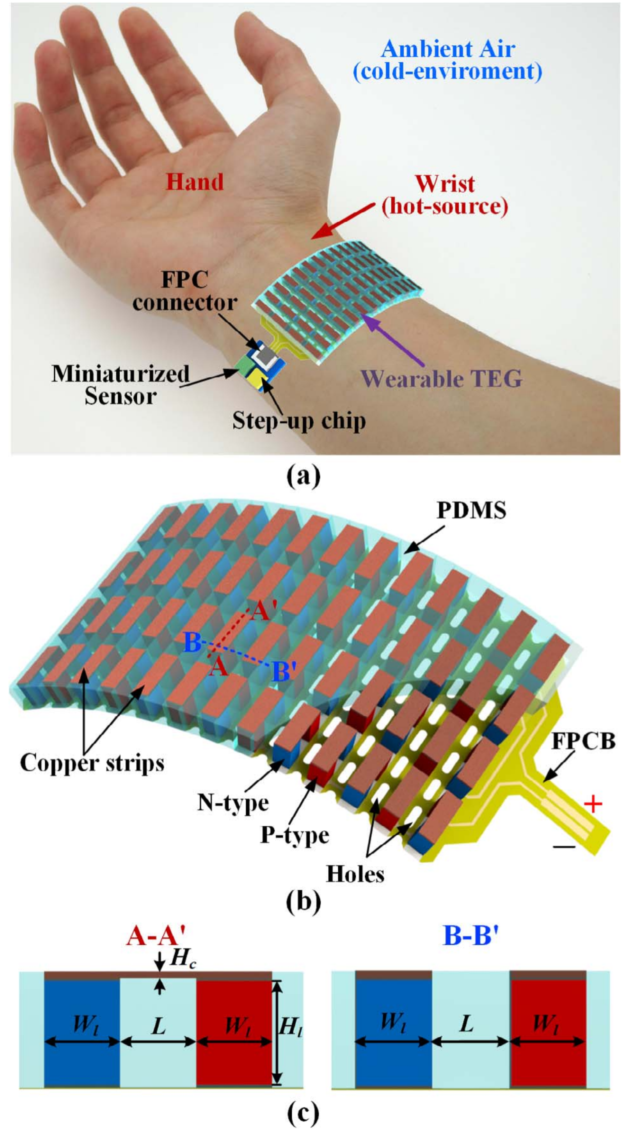

Fig. 1. Schemetic view of (a) the wearable TEG worn on the wrist to power a motion monitoring sensor, (b) the structural design of the TEG, (c) cross-sectional views and structural parameters of the A–A′ and B–B′ sections.

To harvest body heat, high efficiency in the heat conversion and harvesting, and sufficient flexibility represent the two general requirements for the structural design of a wearable TEG. Fig. 1(b) shows the structural design of the TEG: it has 52 pairs of rectangular-shaped P-type and N-type thermoelectric legs. The overall dimensions are about 26.5 mm in width and 43.5 mm in length. The thermoelectric legs are connected in series and thermally in parallel by the top copper strips and bottom flexible printed circuit board (FPCB). As shown in Fig. 1(b), these 52 pairs of P-type and N-type thermoelectric legs are aligned into 4 columns and 13 rows. The thermoelectric legs are connected to the copper strips and FPCB with soldering. For the designed TEG, the bottom FPCB is coated with a thin film of polyimide (PI), which can insulate the TEG from the skin surface of the wrist. Also, to enhance flexibility, several holes are designed into the FPCB, which can also improve the heat transfer from the skin to the device. To protect the