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Design and Fabrication of Wearable Thermoelectric Generator Device for Heat Harvesting

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***Abstract*—This letter presents a novel wearable thermoelectric generator (TEG) device for powering electronics by harvesting human body heat. The structural design of the TEG device consists of 12 thermoelectric modules, which are connected by copper strips electrically in series and thermally in parallel. A flexible printed circuit board with special hollows' design is utilized as the bottom electrodes and substrate to enhance the flexibility of the device. The fabrication procedure to make this TEG device is then described. The hot- and cold-sides of TEG are soldered by a thin layer of $Sn_{96.5}Ag_3Cu_{0.5}$ and $Sn_{42}Bi_{58}$, respectively. Therefore, the developed TEG device features both high flexibility and excellent performance for heat harvesting. Experimental characterization results demonstrated that the TEG device can achieve 23 μW power and 4.75 μW/cm^2 power density at a temperature difference of 35 K. After wearing on human wrist, this TEG device can generate an open-circuit voltage of 10.5 mV, and the ability of using this TEG for powering a light emitting diode has been demonstrated. Results indicated that the developed wearable TEG device could be used for powering of wearable electronics and/or sensors.**

***Index Terms*—Human body heat, power, thermoelectric device, voltage, wearable.**

I. Introduction

In THE past decade, thermoelectric generators (TEGs) have been utilized to harvest the waste heat and energy in industry applications [1], [2]. The TEGs have the abilities to convert the heat into electricity based on Seebeck effect [3]. Body wearable and/or implantable sensors and electronics can be used for health monitoring, whereas additional power supply modules are required and limit the applications of these sensors and electronics for a long-time operation [4]. As for human body, it can be served as a stable and endless natural heat source. Therefore, many researchers have been attracted to the development of wearable TEGs to harvest human heat energy for the battery of electronics and/or sensors [5], [6].

Among the developed wearable TEGs, there are two types of structural designs: rigid and flexible. For rigid TEGs, cuboid shaped thermoelectric legs are usually connected by copper strips, and then sandwiched by aluminum oxide (Al_2O_3) ceramic plates [7], [8]. Wang *et al.* [7] developed a full-fledged miniaturized TEG, the thermopiles were fabricated by using a surface micromachining process. These thermopiles were attached to a silicon chip by flip-chip bonding process. Hyland *et al.* [8] proposed a three-layered TEG, it consisted of two rigid heat spreaders made of copper. One copper spreader was put on the top, the other one placed on the bottom of the thermoelectric legs. A thin-layer of polydimethylsiloxane (PDMS) on the bottom heat spreader was used to block the heat loss into ambient air. However, these TEGs usually have rigid ceramic plates and thermoelectric legs, which are not suitable for wearing on the curved surfaces of body, such as wrist, finger, and etc. For flexible TEGs, both in-plane [9], [10] and cross-plane [11] structural designs are utilized. For the in-plane structure, the thermoelectric legs are arranged parallel to the substrate, such as those in the thin-film TEGs. For example, Kim *et al*. [9] developed an in-plane flexible TEG based on the carbon nanotube (CNT) mats. Experimental results showed that this TEG can be used for the power supply of a glucose sensor. Madan *et al*. [10] presented a series-parallel prototype of TEG device, it has 50 thermoelectric legs which are printed on a polyimide (PI) substrate. The TEGs with in-plane structure cannot achieve large temperature difference, thus the generated power and power density are relatively low. For cross-plane structure, the thermoelectric legs are arranged perpendicular to the substrate. Suemori *et al*. [11] proposed a flexible and lightweight TEG device on a polyethylene naphthalate (PEN) substrate, the flexible CNTs and polystyrene (PS) materials have been utilized for the structural design. Results showed that the developed TEG device can be bent into a curved surface with a radius of curvature of 2.0 mm. Comparing these two types of structural design, the in-plane TEGs usually have greater internal resistance. Therefore, the structural design of a cross-plane wearable TEG device with high flexibility and stability for human body heat harvesting becomes the main goal of this research.

For cross-plane TEG device, the rigid thermoelectric legs can be printed [12] and soldered [13], [14] onto a flexible substrate. Siddique *et al*. [12] proposed a manual dispenser printing method to synthesize and fabricate the flexible TEG. Due to the thermoelectric materials are mixed with polymers, the figure of

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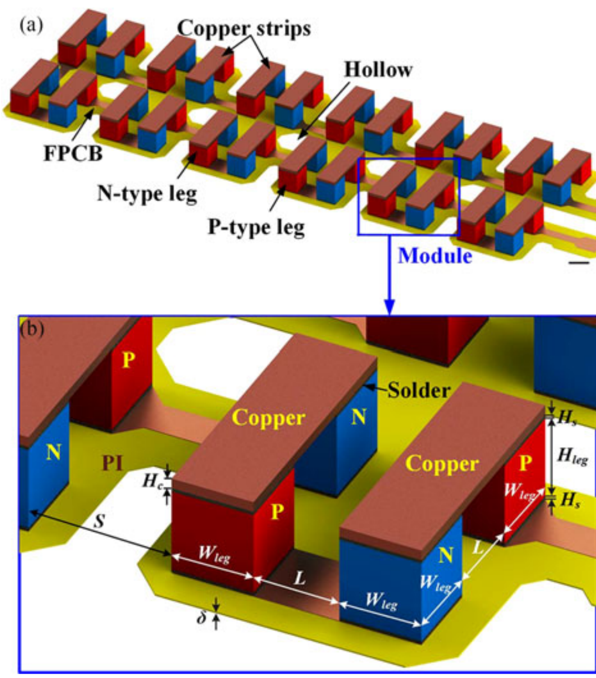


Fig. 1. Structural design of wearbale TEG device: (a) schematic view, (b) close-up view of one thermoelectric module.

merit (*ZT*) value of thermoelectric legs is relatively low, thus the measured performance of the developed TEG is not high enough for real application. Misra *et al.* [13] and Liu *et al.* [14] utilized the soldering process to fabricate the cuboid-shaped thermoelectric legs onto flexible printed circuit board (FPCB). The fabricated TEG device has greater strength and stability, higher performances could also be achieved. As for the soldering of thermoelectric legs at the cold- and hot-sides, the selection of the solders and fabrication procedures may have great effects on the performance of the TEG, such as thermal contact resistances at the interface layers. Therefore, the solder material selection and soldering procedure for the designed wearable TEG device is another goal of this research.

In this letter, we present a novel wearable TEG device to harvest human body heat for powering electronics. The structural design and fabrication procedure of the TEG device are firstly described. Then, experimental characterization of the performances of the TEG device is carried out. This is followed by human wrist wearing experiments for powering electronics. Finally, conclusions and future work are conducted.

II. Wearable TEG Design

The schematic view of the proposed of TEG device is shown in Fig. 1(a), it consists of twelve thermoelectric modules. Each module has two pairs of thermoelectric legs (Fig. 1(b)), which are connected by copper strips electrically in series and thermally in parallel. Underneath the thermoelectric modules, a thin-layer of FPCB with several hollows' design is utilized as the bottom electrodes. The FPCB with hollows design as the substrate can enhance the flexibility of the TEG device for human body wrist wearing applications. The thin-layer of PI film placed in the FPCB can be used for the connection of human wrist, it can also prevent the electrical contact between the device and skin.

Geometrical details of the thermoelectric module with two-pair of thermoelectric legs are illustrated in Fig. 1(b). Both P- and N-type thermoelectric legs have the same cuboid-shape with height of H_{leg} and bottom length of W_{leg}. The distances between thermoelectric legs in each module and adjacent module are marked as *L* and *S*, respectively. The thicknesses of the cold-side copper strips and solders are H_c and H_s, respectively. And the thickness of the PI film in FPCB substrate is δ. For the structural design of TEG device, the copper strips and solder layers have much higher thermal and electrical conductivities and smaller thicknesses than that of P- and N-type thermoelectric legs. Thus, the thermal and electrical contact resistances of these components should be small. Therefore, the effect of H_c and H_s on the performance of the TEG can be neglected. For the thermoelectric legs with larger W_{leg} and H_{leg}, most of heat will be transferred through these legs and used for greater voltage generation. Then the relatively larger thermoelectric legs should be adopted. As for the distances *L* and *S*, a lower *L* can also reduce the heat loss into ambient air and in turn generate higher voltage and power. Also, a bigger *L* and *S* can improve the flexibility of the TEG device, but may reduce the power density. Therefore, optimal structural design of the TEG device need to be conducted to maximum the performances of the TEG for specific wearable application.

The working principle of the TEG can be explained as below: during the application of the wearable TEG, the bottom surface of the device contacts with the human skin, which can be seen as a heat source. The top surface of the TEG will expose to ambient air and acts as the cold-side. The temperature differences between the hot- and cold-sides will lead to a heat flow through the TEG device. Thus, a voltage can be generated based on the Seebeck effect in P- and N-type thermoelectric legs, which could be utilized for powering of wearable electronic devices or sensors.

III. Fabrication

Prior to the fabrication, thermoelectric legs need to be manufactured. In this study, the $Bi_{0.5}Sb_{1.5}Te_3$ and $Bi_2Se_{0.5}Te_{2.5}$ thermoelectric materials [15] are selected and utilized to fabricate P- and N-type thermoelectric legs, respectively. The dimensions of the cuboid-shaped thermoelectric legs are controlled as $W_{leg} = 1.15$ mm in width and $H_{leg} = 1.20$ mm in height. The distances between thermoelectric legs in each module and adjacent module are set as $L = 1.2$ mm and $S = 3.8$ mm, respectively. Then good flexibility of the TEG can be achieved without sacrificing much power generation.

The material properties of the selected thermoelectric materials have been characterized in our former research [15]. At room temperature (300 K), the Seebeck coefficient (α) and electrical resistivity (γ) of $Bi_{0.5}Sb_{1.5}Te_3$ thermoelectric legs are measured as 188 $\mu V \cdot K^{-1}$ and $9 \times 10^{-6}\ \Omega \cdot m$, respectively. For the $Bi_2Se_{0.5}Te_{2.5}$, the values of α and γ are $-228\ \mu V \cdot K^{-1}$ and 1.49

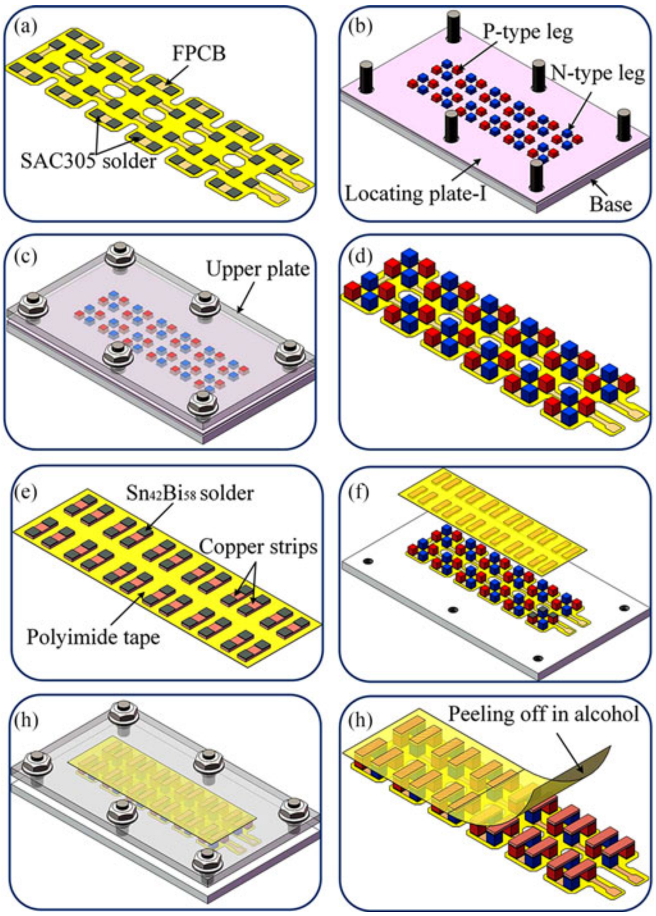


Fig. 2. Fabrication process of wearble TEG device: (a) printing SAC305 solder paste on FPCB, (b) placing thermoelectric legs through the locating plate, (c) covering upper plate and soldering, (d) the fabricated hot-side of TEG, (e) printing $Sn_{42}Bi_{58}$ solder paste on copper strips and glued by PI tape, (f) placing copper strips on the thermoelectric legs, (g) covering upper plate and then soldering, (h) peeling off the PI tape in alcohol.

$\times$ 10^{-5} Ω·m, respectively. The fabricated thermoelectric legs have almost same thermal conductivity (*k*) of 1.1 $\mathrm{W \cdot m^{-1} \cdot K^{-1}}$. Therefore, the figure of merit (*ZT*) of P- type and N-type thermoelectric legs are calculated as 1.1 and 0.9, respectively.

In order to reduce the fabrication error, for the selection of solder material, $Sn_{96.5}Ag_3Cu_{0.5}$ (SAC305) and $Sn_{42}Bi_{58}$ (provided by Vital Chemical Development Industry CO., LTD) are utilized for the soldering of hot- and cold-sides of the TEG, respectively. These two solders have different melting points of 217 °C and 138 °C, respectively. Therefore, during vacuum soldering processes, the soldering temperatures of these two solders are set as 260 °C and 180 °C, respectively.

To fabricate the TEG device, a four-step procedure (as in Fig. 2) is developed and described as follows:

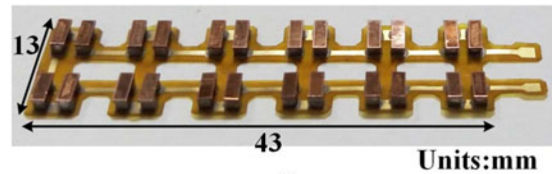
Step 1 – Bottom electrodes and substrate fabrication: firstly, a thin-layer of FPCB with 25 μm-thick PI film is fabricated and utilized as the substrate. Several hollows are cut out from the FPCB to improve the flexibility. Secondly, a copper film is printed on the FPCB as the bottom electrodes. Then, a layer of SAC305 solder paste with a thickness of 0.1 mm is printed onto the copper film by screen printing process through a designed stainless-steel mask, as shown in Fig. 2(a).

Step 2 – Thermoelectric legs soldering: firstly, the FPCB is fixed onto a flat metal base, a stainless-steel locating plate is placed on the top surface. The locating plate with square hollows is used to position the thermoelectric legs during soldering, as in Fig. 2(b). Then, an upper plate is placed on the top to apply a uniform pressure on thermoelectric legs during soldering, as in Fig. 2(c). Secondly, the P- and N-type thermoelectric legs are soldered onto the FPCB in a vacuum oven at a temperature of 260 °C for 3 mins. This is followed by removing all the plates and leaving the P- and N-type thermoelectric legs soldered onto the FPCB, as in Fig. 2(d).

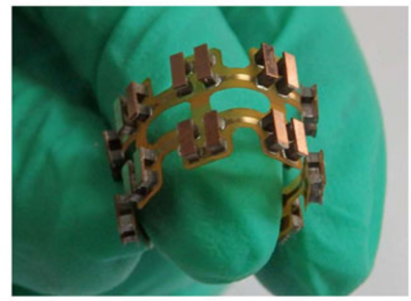
Step 3 – Upper electrodes preparation: the upper electrodes need to be soldered onto the top surface of the thermoelectric legs. For positioning copper strips on the site of thermoelectric legs, 0.3 mm-thick copper strips are utilized and placed into a 3D printed ABS mold, and then glued by a PI tape. Then, the $Sn_{42}Bi_{58}$ solder paste is printed on the copper stripes by screen printing process, as shown in Fig. 2(e).

Step 4 – Assembly: the prepared PI tape with copper strips is placed on the top surface of the thermoelectric legs, as in Fig. 2(f). An upper plate is covered on the PI film (Fig. 2(g)), as the same as in Step 2. Then, we put this whole device into a vacuum oven for soldering at 180 °C for 3 mins. Then, the copper strips will be correspondingly soldered onto the top surface of the thermoelectric legs. After cooling to room temperature, the base and upper plates are removed. Lastly, this device is put into the alcohol solution for 10 mins to peer off the PI tape, as illustrated in Fig. 2(h).

Fig. 3(a) shows the photograph of final fabricated TEG device, the overall area of the device is about 43 mm $\times$ 13 mm. Due to the thin FPCB substrate with hollows' design, the TEG device has a remarkable flexibility. Even it can be wrapped on a finger (Fig. 3(b)), thus the bending radius of curvature could be smaller



(a)



(b)

Fig. 3. Fabricated wearable TEG device: (a) photograph and (b) wrapping on the finger.

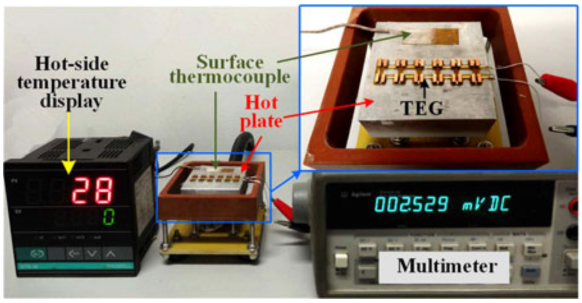


Fig. 4. Experimental setup to characterize the output performance of the wearable TEG device

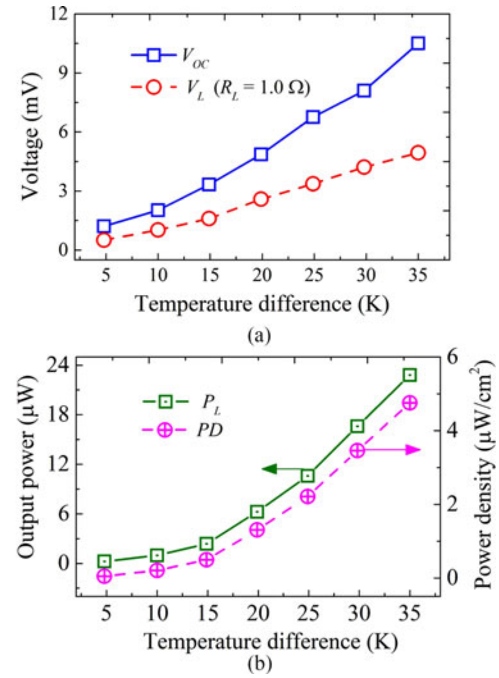


Fig. 5. Output performance of the wearable TEG device under variable temperature difference (ΔT): (a) open-circuit voltage (V_{OC}) and loading voltage (V_L), (b) output power (P_L) and power density (*PD*).

than 5 mm and would be suitable for wearing on the curved wrist surface.

IV. Experiments Characterization

A. Experimental Setup

After fabrication of the wearable TEG device, the output performances need to be characterized. Experimental setup to study the performance of the TEG device is shown in Fig. 4, where a heating platform is utilized as the heat source. The TEG device was placed on the heating platform, the copper strips at the cold-side were exposed to ambient air. A K-type surface thermocouple (SA1XL-K, Omega Inc.) was attached to the heating platform and used to measure the hot-side temperature (T_h). The room temperature (T_{air}) was measured by an air thermometer, the value of T_{air} is commonly a little larger than that of the cold-side temperature (T_c) [15]. In this study, the temperature difference (ΔT) was calculated as $\Delta T = T_h - T_{air}$, which can reflect the temperature differences between the hot- and cold-sides of TEG. By setting different T_h, the temperature difference (ΔT) can be controlled and adjusted.

During the experiment, the generated voltages are measured by using a digital multimeter (34401A, Agilent Technologies), as shown in Fig. 4. In this study, both the open-circuit voltage (V_{OC}) and loading voltage (V_L) are measured. To measure the V_L, the loading resistance $R_L = 1.0\,\Omega$ is utilized.

For the TEG device, internal resistance (R_{in}) is a critical parameter to affect the voltage and power generation. After measuring the V_{OC} and V_L, the R_{in} can be calculated as

$$R_{\text{in}} = \frac{(V_{OC} - V_L) \times R_L}{V_L} \tag{1}$$

where R_L is the loading resistance, here the value is set as 1.0 Ω.

The output power (P_L) is determined by the R_{in}, R_L, and measured V_{OC}

$$P_L = \frac{V_{OC}^2}{(R_{\text{in}} + R_L)^2} \times R_L \tag{2}$$

Then, the power density (*PD*) can be calculated as the output power (P_L) divided by the area (A) of the TEG. Here, for the developed TEG device, the bottom surface area (A) is calculated as 5.59 ($= 4.3 \times 1.3$) cm^2.

B. Characterization Results

During the experiments, the room temperature (T_{air}) was measured with a value of 22 °C and the heating platform was heated from 27 °C to 57 °C. Thus, the ΔT varied from 5 K to 35 K. Fig. 5(a) shows the measured results of V_{OC} and V_L when $R_L = 1.0\,\Omega$. Both the V_{OC} and V_L increased almost linearly as the increasing of ΔT. When $\Delta T = 5$ K, the V_{OC} is 1.2 mV. As ΔT increased 35 K, the measured V_{OC} increased to 10.5 mV. Moreover, the measured V_{OC} is greater than that of V_L under a given ΔT. Typically, the measured V_{OC} is about 1.8 times larger than that of V_L, as shown in Fig. 5(a). By using Eq. (1), internal resistance (R_{in}) of the TEG device is calculated with an average value of 1.2 Ω.

Also, based on the measured V_{OC} and V_L and calculated $R_{\text{in}} = 1.2\,\Omega$, the output power ($P_L$) and power density (*PD*) can also be calculated. Fig. 5(b) shows the calculated P_L and *PD* versus ΔT. As the increasing of ΔT, the output power is also increased. The same trend can be observed for *PD*. When $\Delta T = 5$ K, the P_L and *PD* are only 0.2 μW and 0.05 μW/cm^2, respectively. As ΔT increased to 35 K, the calculated P_L is greatly enlarged with a value of 23 μW, and *PD* is calculated as 4.75 $\mu\text{W}/\text{cm}^2$, as shown in Fig. 5(b).

Thus, both the output voltage, power, and power density will be increased as the increasing of the temperature differences between the hot- and cold-sides of the TEG device. For the purpose of enhancing output performance, several methods to enlarge the temperature difference have been proposed: 1) the structural design of a heat sink module at the cold-side of the TEG device has been widely utilized [16]. The heat sink module can enlarge the heat dissipation into ambient air, thus increasing the temperature difference to achieve a higher output voltage and

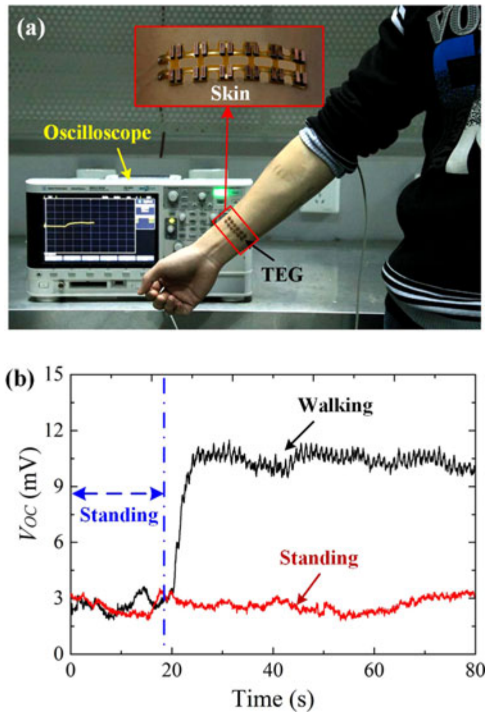


Fig. 6. (a) Experimental setup to measure the performance of the wearable TEG device when worn on the wrist; (b) measured results of the open-circuit voltages under two kinds of working conditions.

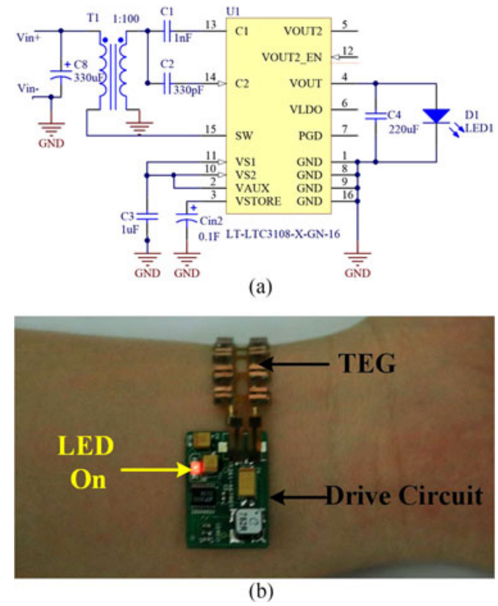


Fig. 7. (a) Schematic diagram of the DC-DC drive circuit for the wearable TEG device, (b) TEG device worn in the wrist for powering of a LED.

power generation; 2) increasing the dimensions of thermoelectric legs, typically in the height direction, can also enlarge the temperature difference, and in turn enhance the performance for heat harvesting; 3) strengthening the heat convection at the cold-side of the TEG device is also an effective way to generate greater output voltage and power.

V. Human Wrist Wearing Experiments

A. *Human Body Heat Harvesting*

After characterization, the developed wearable TEG is worn on a human wrist for body heat harvesting, as shown in Fig. 6(a). During the experiment, the temperature of the wrist skin is firstly measured by using a K-type surface thermocouple (as in Fig. 4) with the data of 27 °C. The ambient temperature is measured by the air thermometer with a value of 19 °C. Thus, the temperature difference between the skin and ambient air is about 8 K. The output voltage is recorded by using an Agilent oscilloscope (MSO-X 2022A), as shown in Fig. 6(a).

During the experiment, the operator under two kinds of working conditions was performed. **Condition 1** – static standing: after wearing the TEG device on the wrist, the operator kept standing for 80 s; **Condition 2** – walking: at first, the operator kept standing for 20 s, and then walking in a natural gait for 1 min. In these two conditions, the convection coefficients of walking and standing are $75\,\mathrm{W \cdot m^{-2} \cdot K^{-1}}$ [17] and $20\,\mathrm{W \cdot m^{-2} \cdot K^{-1}}$ [18], respectively.

The results of the measured V_{OC} under static standing and walking conditions are plotted in Fig. 6(b). At static standing condition, the generated V_{OC} has almost a constant value of about 3.0 mV. Under walking condition, the measured V_{OC} is greatly increased from 3.0 mV (Phase I – standing) to 10.5 mV (Phase II – walking). Compared to static standing, the wearable TEG device under walking condition can generate much higher (about 3.5 times) open-circuit voltage. The reasons can be explained as: during walking condition, the arm is swinging. It will enlarge the convection coefficient at the cold-side of the TEG device. Our former research has demonstrated that the TEG device under higher convection coefficient at the cold-side could generate greater open-circuit voltages [15].

In Fig. 6(b), we can see that the measured V_{OC} under walking condition has a relatively small variation. Under walking condition, the V_{OC} increased dramatically at first 5 s, then reached to a maximum value and kept stable. In this condition, the convection coefficient at the cold-side of the TEG can be assumed constant and has a value of $75\,\mathrm{W \cdot m^{-2} {\cdot} K^{-1}}$. Thus, the generated V_{OC} is also constant (=10.5 mV), as shown in Fig. 6(b). Results indicated that the wearable TEG device under walking condition can generate higher voltage during wrist wearing application.

B. *Wrist Wearing Application*

The wearable TEG device is developed for powering electronics and/or sensors for health monitoring and movement detection [19]. In this study, a light emitting diode (LED) is selected and utilized as the operating device. A DC (direct current) – DC drive circuit is designed and illustrated in Fig. 7(a). For this LED device, the minimum required input voltage is 20 mV. Here, the voltage generated by the TEG device is magnified by 100 times greater through a transformer. For the drive circuit, the LTC3108 chip is utilized as the step-up chip, and the output voltage can be selected at different foots. As in Fig. 7(a), the VLDO (Voltage of low dropout linear regulator) foot with output voltage of 2.2 V is selected. This value should be sufficient for powering the LED. The final fabricated drive circuit has small dimensions of about 18 mm in width and 25 mm in length, as shown in Fig. 7(b).

Indeed, due to the proposed TEG device has only 12 thermoelectric modules, the generated open-circuit voltage is relatively low, as shown in Figs. 5(a) and 6(b). To increase the temperature differences, we performed the experimental tests outdoors. The ambient temperature measured by the air thermometer is only 10 °C, whereas the wrist skin has a temperature of 27 °C. Thus, the temperature difference is 17 K. The LED can be successfully lit up by wearable TEG device, as shown in Fig. 7(b).

Thus, the generated open-circuit voltage should be larger than 20 mV, which is the minimal required voltage for LTC3108 chip of the circuit for LED working. Therefore, results obtained in this letter demonstrated the ability of the developed wearable TEG device could be worn on the human wrist and used for powering the electronics.

In future, for powering the electronics and sensors which require higher voltage and more functions, the developed TEG device and its drive circuit still need improvement. Firstly, only 12 thermoelectric modules are utilized in the prototype. Increasing the numbers of thermoelectric modules for the structural design of the TEG device could enhance the voltage and power generation. Thus, more thermoelectric modules, such as 48 or 64 modules, could be utilized for the improved TEG device in future. Secondly, optimal structural design of the wearable TEG device needs to be conducted. The present structural design of the TEG device is far from optimal. Especially the heat sink module at the cold-side has not yet applied. Also, the distances between adjacent thermoelectric legs can be decreased for reducing the heat loss between thermoelectric legs. Thirdly, the minimal required input voltage and power to drive the step-up chip and circuit can be further lowered, the dimensions of the drive circuit can also be reduced.

VI. Conclusion

In this letter, a wearable TEG device for powering the electronics by harvesting human body heat is developed. The structural design, working principle, and fabrication procedure of the wearable TEG device are presented. The FPCB with special hollows design as the flexible substrate can enhance the flexibility of the TEG device for wearing application. The developed wearable TEG device has remarkable flexibility and can be wrapped on a finger with radius of curvature lower than 5 mm. Then, the performance characterization and human wrist wearing experiments are carried out. The TEG device has relatively low internal resistance of 1.2 Ω, and can generate an open-circuit voltage of 10.5 mV at $\Delta T = 35$ K. The corresponding output power and power density are calculated as 23 μW and 4.75 $\mu\mathrm{W/cm}^2$, respectively. Wrist wearing experiments showed that the TEG device can generate higher voltage and power under walking condition than that under static standing. By designing the driven circuit, the TEG device worn in the wrist can be utilized to power the LED successfully by harvesting body heat energy.

Results obtained in this research open the opportunity to develop wearable TEG device for powering electronics and/or sensors by harvesting human body heat. Future work will focus on optimal structural design of the wearable TEG device to maximize the voltage and power generation for human body health monitoring and motion detections.

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