WEARABLE THERMOELECTRIC GENERATOR FOR HUMAN CLOTHING APPLICATIONS

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ABSTRACT

In this study, a wearable thermoelectric generator (TEG) in the flexible fabric is proposed for converting human body heat energy to electrical energy. The wearable TEG is composed of a flexible fabric material, thermoelectric columns (Bi_2Te_3) and electrical connection based on conductive fabric component. The proposed TEG showed the flexibility and the wearability suitable to be applied to the human body. The TEG was fabricated dispenser printing, and the fabricated device converted applied contact heat into electrical energy (0.98 µV/K). When the TEG applied to the human body, the measured output power was 178 nW in ambient temperature of 5 °C.

KEYWORDS

Wearable thermoelectric generator, flexible, energy harvesting, human body, dispenser printing

INTRODUCTION

The increasing use of portable electronic devices and medical implants, the issues such as auxiliary power and wireless power is more important in recent years. An alternative approach is to extract various energy sources from outside [1]. Of these, body heat energy generator can harvest electrical energy at anytime and anywhere [2]. The body heat energy is converted into electrical energy using a thermoelectric generator (TEG). The TEG has many advantages such as compact, silent and high reliability. In order to harvest body heat, the energy generator needs to have flexibility and wearability for guaranteeing human activity.

There have been various researches about flexible TEGs that are realized on a polymer substrate. The common approach is fabricated by evaporating thin films on flexible substrate [3-4]. J. weber et al. used coin-size coiled-up polymer foil TEG for wearable electronics [5]. Wulf glatz et al. used a combination of copper and nickel in a thick flexible polymer mold formed by photolithography [6]. Another approach is dispenser printed planar thermoelectric devices [7]. While most flexible TEGs have no consideration of wearable form and their flexibility is limited by the thickness of the substrate. And these techniques require a complex fabrication of the device.

In this research, a wearable TEG in fabric components is proposed for applying to human body. The proposed wearable TEG offers flexibility through the integration of a textile and a polymer structure. The use of conductive thread and fabric structure allows the TEG to have the wearability. To simplify the fabrication process, we use the dispenser printing method. By a simple process, large-scale production is possible. The Energy conversion device using wearable TEG is expected to be available in a variety of applications. These include mobile phone battery charging, real-time checking of the status of the body and the positioning signal in emergency situation.

We fabricate a prototype through the simple process, and tried to test the performance when applied to a real human body. In the following sections, the proposed wearable TEG of the design, fabrication steps and results as well as discussions on the suitability of applying human body are presented.

DESIGN

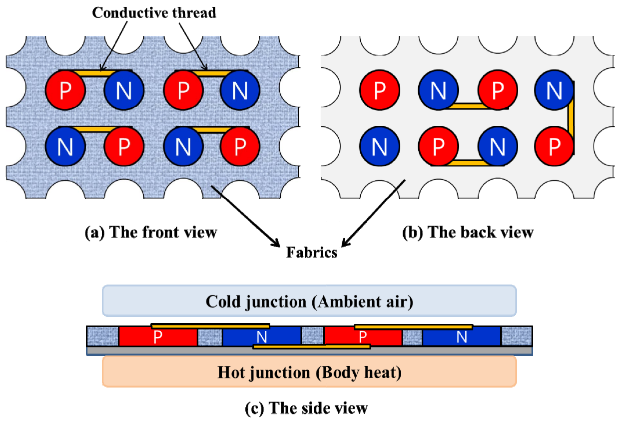

Figure1. The concept views of the proposed wearable TEG device. (a) the front view, (b) the back view and (c) the side view.

Thermoelectric generators (TEGs), i.e. the using the Seebeck effect, the temperature difference between two junctions is converted to electric energy. The open circuit voltage being converted is proportional to Seebeck coefficient α, number of thermocouples n and the temperature difference ΔT.

$$V_{output} = n\alpha\Delta T \quad (1)$$

The maximum output electric power with optimal impedance matching given by

$$P_{MAX} = VI = \frac{{V_{output}}^2}{4R_0} = \frac{(n\alpha\Delta T)^2}{4R_0} \quad (2)$$

where R_0 internal resistance of thermopile.

Fig.1. shows the concept views and the working principle of the proposed wearable TEG device. The polymer film is attached to the fabric structure. The fabric structure has windows for inserting the thermoelectric columns of p- and n-type materials (Bi_2Te_3). Hot junction and cold junction are arranged each to the top side and the bottom side, each thermocouple is electrically connected by conductive fabric fiber, which silver contained. The bottom side contacts to the human body (25~35 °C). The

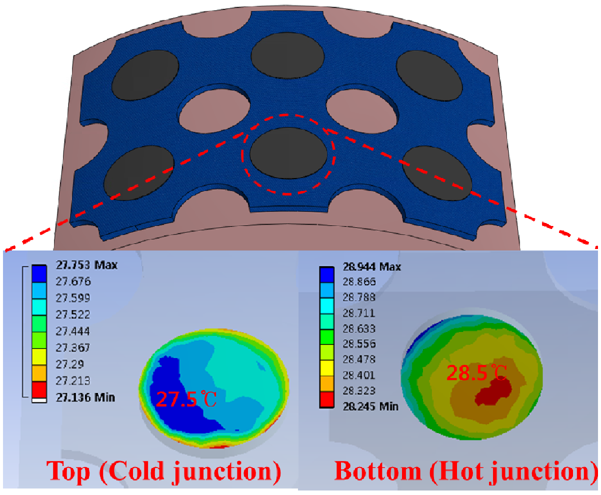

Figure2. FEM simulation results of the thermoelectric element on the human body ($T_{ambient\_air}$=15 °C, T_{human_body}=32 °C).

top side is exposed to the outside (-20~40 °C), there occur heat exchange with ambient air. The top surface has a relatively low temperature and maintains the temperature difference with the bottom. When the outside temperature is lower, the TEG can get a higher power.

Fig.2 shows the simulation result of the temperature difference between top and bottom side when the wearable TEG is attached on the human body. In the simulation, it was assumed that the temperature of the human body and ambient air is 32 °C and 15 °C, respectively. When the difference between the body temperature and the outside temperature is 17 °C, temperature difference between hot and cold junction is about 1 °C. The simulation result of a small device shows that the temperature difference between each side of the TEG is enough to generate electrical energy on the human body. All simulation results were made using the ANSYS package and it is consistent with theoretical calculations.

FABRICATION AND EXPERIMENT

The wearable TEG is fabricated by dispensing printing. The conventional methods of sputtering or evaporation are expensive for future mass market products [8-9]. Dispensing printing does not require expensive thin film techniques. Therefore, there is an advantage to low cost and batch fabrication process.

Fig.3 shows the fabrication processes. A polyester-based fabric, commonly used for clothing, is flexible and lightweight material. The conductive fiber, made of silver-plated, was used to fix to the fabric layer for electrically connecting. The polymer film was attached to the fabric layer for substrate of thermoelectric elements and electrical isolation between the thermocouples and the skin. The prepared printable ink of Bi_2Te_3 was inserted into the windows of the fabric layer and cured.

The weaving process is needed for conductive fiber fixing to the substrate fabric. First, Fix to the substrate with conductive thread in a line, and then each section cutting. Thermoelectric elements have to be connected up and down electrically in each section.

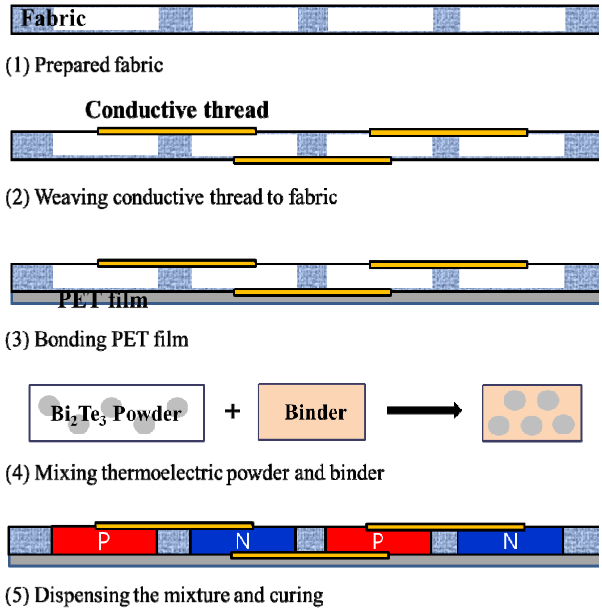

Figure3. Fabrication process for a dispenser-printed thermoelectric device.

Complex thermoelectric materials such as Bi_2Te_3, Bi_2Se_3, or Sb_2Te_3 have a high thermopower at room temperature [10]. In this research, thermoelectric material Bi_2Te_3 powder (100 meshes) of the n- and p-type was using to consist of a thermocouple. By adjusting precise stoichiometric ratio can get the n-and p-type character. We have used the each type of the products sold in the market. A mixture of the ceramic binder and the Bi_2Te_3 powder, inject to using a dispenser in each hole. For high strength of the TEG, it needs curing at room temperature for 24 hours and sintering at 100 °C for 2 hours. The process of relatively low temperature can make simple manufacture and there is no damage to the fabric. The used binder is excellent electrical performance and durable to suitable for clothing.

Relevant dimensions of the fabricated TEG are shown in table 1. The TEG included twenty thermocouples in an 80 mm × 45 mm area. Each thermopile radius is 5 mm and thickness is 0.5 mm. The total internal resistance of the TEG is about 300 ohms. Fig.4 shows the fabricated wearable TEG and photos of the device applied to the human body. As shown in figure, the fabricated TEG was highly flexible and durable.

Table1. Table of measured material properties and design parameters.

Parameter	Description	Magnitude
Number of TE couples	Number	20
Fabric Substrate	Length x Width x Thickness	80mm x 45mm x 0.5mm
TE	Radius	5mm
	Thickness	0.5mm
Total Resistance	Resistance	300Ω

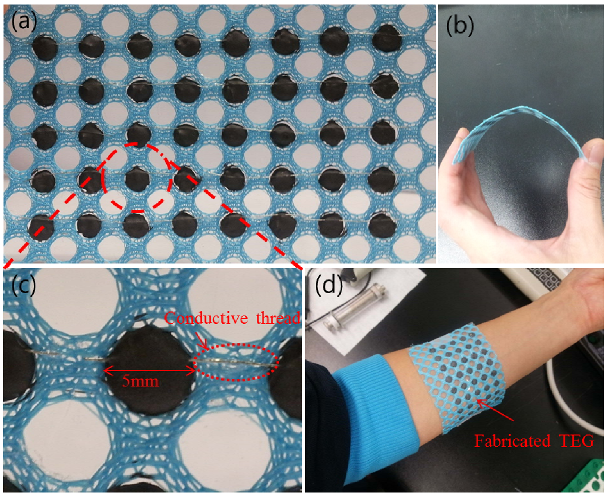

Figure4. (a) Images of printed 20-couple thermoelectric device. (b) Demonstration of bending wearable thermoelectric generator by hand. (c) Close-up view of the dispenser printed thermocouples and (d) TEG being worn on the human body.

In order to test the thermoelectric property of the TEG, we set up the thermal experimental equipment. The temperature difference can be adjusted via a hot-plate and a Peltier cooler. The wearable TEG put it on the hot-plate, and then temperature and voltage change were measured by the temperature sensor and the oscilloscope. For optimal output, load resistance was matched to the internal resistance (300 ohms). The open circuit voltage as a function of temperature difference ΔT is recorded. And then temperature difference is from 3 °C to 30 °C.

The following experiment was to verify the performance in real-world environments. The thermoelectric devices attached to the chest, and then output power was estimated at the indoor environment (about 25 °C). Another experiment was conducted in the cold outside environment (about 5 °C).

RESULTS AND DISCUSSION

Fig.5-(a) and (b) shows the measured output voltage and power as a function of the temperature difference between each junction, respectively. The prototype generates, at 30 °C temperature difference, an open voltage about 25 mV with optimal impedance matching. And then an electrical output power is up to 2.08 μW. Fig.5-(a) shows the linear dependence between the voltage and the temperature difference of the wearable TEG. The thermopower can be calculated from the slope, which leads to a value of about 0.98 mV/K.

Table 2 shows the measured output voltage and power when the fabricated TEG was worn on the chest of the human body. The measured human body temperature was about 32 °C. When ambient air temperature was 25 °C, the generated output power of the TEG was about 15 nW. The output power of the TEG increased to 178 nW when ambient air temperature decreased to 5 °C.

As a result of applying to the human body, it was not better than the results of the laboratory environment. The reason seems to that the skin temperature was changed quickly according to ambient temperature. The prototype used to thin polyester base fabric. But if using the good insulation material for a substrate fabric, efficiency will be higher. The prototype in this work has the loss due to the electrical contact resistance between the conductive fiber and dispenser printed thermoelectric elements. It will be able to get better performance by using a more superior electrical performance binder.

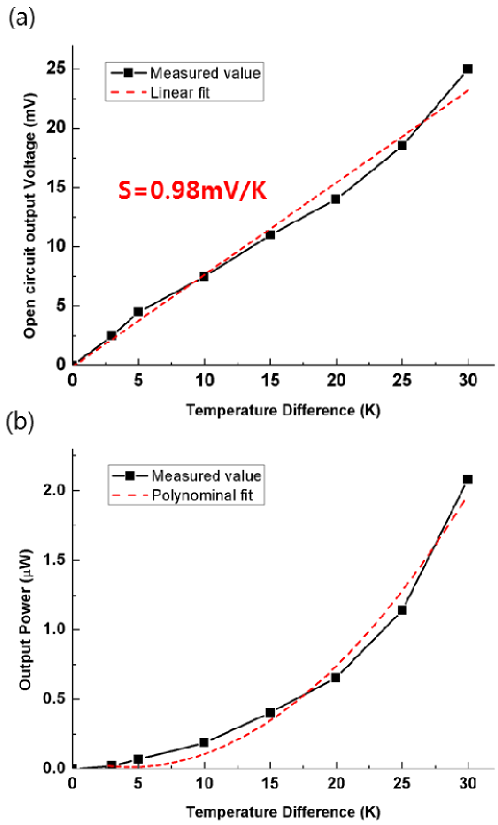

Figure5. Output results of the 20-couple prototype generator (a) open circuit output voltage and (b) power as a function of top-bottom temperature difference.

Table2. The energy transduction results of the wearable TEG on the human body.

Body Temperature (℃)	Ambient Temperature (℃)	Output Voltage (mV)	Output Power (nW)
32	25	2.1	15
32	5	7.3	178

CONCLUSIONS

In this work, we present the possibility of clothing type energy harvester using the wearable TEG. The prototype has been applied to an actual fabric, and tested the thermoelectric performance. The proposed TEG showed the flexibility and wearability suitable to be applied to the human body.

The fabrication process of the dispenser printing was successfully performed. The fabricated TEG consisting of 20 thermocouples has a thermopower output of about 0.98 mV/K and is able to generate a voltage of 25mV at a temperature difference of 30 °C. In actual environment, it can generate up to 178 nW in ambient temperature of 5 °C.

Our future work is focused on improves performance by using excellent thermoelectric materials and a variety of fabrics. And we will develop packaging technique for a more appropriate form of the wearable TEG.

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