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Structural design of a flexible thermoelectric power generator for wearable applications

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HIGHLIGHTS

- A high performance flexible thermoelectric generator (f-TEG) is developed.
- Structural design guideline of the f-TEG for human body application is proposed.
- The highest power (2.28 μW/cm^2) using the f-TEG with no heatsink is achieved.
- The efficiency of power management IC must be included for the f-TEG optimization.

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ABSTRACT

Self-powered wearable electronic devices are expected to be one of the mainstream technologies for future portable electronic systems. As an energy harvester to power wearable electronic devices, a flexible thermoelectric generator (f-TEG) can utilize human body heat as the energy source, creating an ideal solution. The f-TEG can make conformal contact to the human skin and fully utilize body heat with minimal energy loss, while also being comfortable to wear. However, to maximize the power generated by an f-TEG attached to the human body, a careful thermal and structural design analysis of the f-TEG must be carried out. Here, we fabricated flexible thermoelectric generators (f-TEGs) with different device parameters and evaluated their power generating performance using an artificial arm, which was carefully designed to mimic a real human arm. We demonstrated the impact of the f-TEG device parameters on the power generation performance under various circumstances. The experimental results were compared with the theoretical model, and guidelines for an optimum device design in terms of maximizing the generated power density are also presented. Finally, we show that the optimum device structure varies when the efficiency of the power management IC (PMIC) is included in the analysis of the power generation system, which is practically important.

1. Introduction

With the emergence of the Internet of Things (IOT) era, and the widespread use of electronic devices that can communicate anytime and anywhere, interest in wearable electronic systems is also growing. But before wearable electronic systems can be widely introduced, the problem with needing to frequently recharge their batteries must be overcome. The most effective way to solve this issue is to integrate an energy harvester with the wearable electronic device, so that it becomes a self-powered system. With this goal in mind, energy harvesting modules such as solar cells [1,2], vibration-based energy harvesters [3,4], and thermoelectric generators (TEG) [5–10] have all been considered as semi-permanent energy suppliers. Among them, the TEG, which can convert the heat generated by the human body into electricity, is considered a particularly attractive way to realize a self-powered wearable system.

When a TEG is used in a self-powered wearable system, the TEG needs to be flexible in order to provide conformal thermal contact between the human body and the TEG, and this is especially true for a larger sized TEG. In order to realize a flexible TEG (f-TEG) structure, many researchers have focused on flexible TE materials including conducting polymer [11,12], CNT [13], and transition metal

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dichalcogenide (TMDC) [14–16] materials. These materials have shown outstanding performance in flexibility but poor performance in output power density due to a poor power factor and a high contact resistance with metal electrodes. In terms of power output performance, field-proven BiTe-based inorganic materials are preferred, but the problem of material rigidity should still be overcome. Recently, innovative structures to fabricate f-TEGs using inorganic materials have been reported [17–19]. Among the various structures, a f-TEG that eliminates the rigid substrate and fills the empty space with a flexible polymer is advantageous for obtaining a high output as it retains the basic structure of the commercialized TEG [20–22].

Although there have been many reports on f-TEGs, most studies dealing with f-TEGs to date are at the stage of demonstration of the material or a single device. When a f-TEG is used for a wearable application using body heat, only a small temperature gradient is applied across the f-TEG because the surroundings have much larger thermal resistance than the f-TEG between the body and ambient [23]. As such, the f-TEG must be carefully designed and optimized in order to maximize the power generated from body heat.

In this work, we fabricated an f-TEG with commercially available bulk thermoelectric legs and experimentally demonstrated the effect of the f-TEG structure on the output power generated from body heat. The power generation performance of f-TEGs with different leg heights and device fill factors are evaluated and tendencies according to various structural changes are found based on experimental results. With structural optimization, we can obtain a power density of 2.28 μW/cm^2, to the best of our knowledge, which is the highest value among reported flexible TEGs on the human body with no use of heatsink under natural convection. An artificial arm, which was carefully designed to mimic a real human arm, was also devised and made for repeatable and reliable experiments. The thermal model of a conventional TEG was modified and extended to the f-TEG, and the validity of the model was evaluated through a comparison with experimental results. In addition, we provide guidelines for the optimized structure of the f-TEG with consideration of the voltage-dependent efficiency of the power management IC (PMIC), which is practically important for wearable applications.

2. Experimental procedure

2.1. Flexible thermoelectric device

The fabricated f-TEG was simply based on a conventional TEG module structure but without a ceramic substrate. The integration process begins with arranging and bonding the TE legs on patterned copper thin film. After the $Sn_{96.5}Ag_{3.0}Cu_{0.5}$ solder paste was printed onto the copper patterns, N and P types of thermoelectric legs were directly transferred onto the printed solder material, followed by a bonding process in nitrogen ambient *via* a eutectic wafer bonder system. During the bonding process, the temperature of the top and bottom side of the device was ramped up to 260 °C and quickly cooled down after the temperature reached 260 °C. After the bonding process, in order to ensure the mechanical integrity of the structure without a rigid substrate, the empty space in the module was filled with a proprietary polymer material that has a very low thermal conductivity (0.03 W m^{-1} K^{-2}) [24]. A schematic drawing and an actual photo of the fabricated f-TEG are shown in Fig. 1. Since the copper electrodes in the f-TEG structure are exposed, the electrodes will have contact with the human skin. However, this does not cause an electrical short between the electrodes because the electrical resistance of the human skin is much higher than that of the copper electrodes. For the thermoelectric legs, a commercially available material (Kryotherm) with an area of 1.0 mm^2 and two different heights of 0.8 mm and 2.5 mm was used. Sample f-TEGs with 72 couples of thermoelectric legs having different fill factors of 15.1%, 19.8%, and 27.2%, were prepared. Here, the fill factor is defined as the ratio of the overall area of the thermoelectric legs to the total area of the device. The device figure of merit (ZT) of the f-TEG modules was in a range of 0.63–0.64 for the 2.5 mm high device and 0.60–0.62 for the 0.8 mm high device, and the electrical resistance of the module was about 2.14 Ω for the f-TEG leg heights of 2.5 mm and 0.81 Ω for the leg heights of 0.8 mm, respectively (Table S1). The ZT values and electrical resistances were measured using a Z-meter from RMT Ltd.

2.2. Thermoelectric properties

The electrical conductivity and the Seebeck coefficient of the bulk material were measured using a thermoelectric property measurement system (ZEM-3, ULVAC). The thermal conductivity κ of the thermoelectric material was determined based on the relation $\kappa = \lambda C_p D$, where the thermal diffusivity λ, the heat capacity C_p, and the density D were measured using the laser flash method (LFA 457, Netzsch), differential scanning calorimetry (DSC 204F1, Netzsch) and the Archimedes' method, respectively. All of the thermoelectric properties are presented in Table 1.

2.3. Artificial arm

To determine the optimum f-TEG module design through experiments and the heat transfer model, we prepared an artificial arm whose thermal resistance was adjusted to be similar to that of a real human arm. Using the artificial arm made it easy to repeatedly obtain measurements using the same experimental environments. Fig. 3a shows a photo of the outside and inside of the artificial arm. A flexible heater is attached to the inner surface of the artificial arm with a polyimide (PI) film interfacial layer. The artificial skin is made of about 3 mm thick rubber. As illustrated in Fig. 3b, a PI film interfacial layer was used so that the heat resistance between the flexible heater (which mimics the blood vessel in an actual human arm) and the artificial skin could be adjusted, by carefully adjusting the thickness of the PI film, so that it would be similar to the conditions of a human arm.

In a real human arm, the temperature of the blood vessels is considered a heat source with a constant temperature of 37 °C. When the ambient temperature is 25 °C, the skin temperature of the human arm is measured to be 33.9 °C (Fig. 3c). If two thermal resistors are connected in series and the temperatures of both ends are fixed, the thermal resistances of each component can be obtained by measuring the temperature at the interface of the two thermal resistors. Considering this, an artificial arm with a thermal resistance similar to that of a human arm can be prepared by adjusting the temperature of the artificial skin to be 33.9 °C for the same ambient and core temperatures. As shown in Fig. 3d, the temperature of the artificial skin decreases with increasing thickness of the PI interfacial film, due to the increase in total thermal resistance. In our experiment, a 500 μm thick PI film created a thermal resistance that was closest to the case of a real human arm.

2.4. Measuring the power output

To measure the power generated by the f-TEG on the artificial arm, 30 μm flexible graphite sheets with high lateral thermal conductivity (1300 W m^{-1} K^{-1}) were attached to both sides of the f-TEG using a thermal paste with a thermal conductivity of 8.1 W m^{-1} K^{-1}. The output power and the voltage output of the f-TEG were obtained using a Keithley 2425 sourcemeter. Instead of using an external load resistance, we matched the auxiliary external load resistance using the Keithley 2425 sourcemeter, which can extract the output current *vs.* input voltage. An additional explanation of the f-TEG power measurement is described in the Supporting Information. The core and the ambient temperature were monitored using a Keithley 2700 multimeter.