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Design and Performance of Transverse-Type Thin-Film Nano-Thermoelectric Generators

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Abstract. Design methodology and performance of nano thermoelectric generators (nTEGs) using human body heat are investigated for wearable device applications. A transverse type of module suitable for a thin-film thermopile is employed for the nTEGs. It is revealed that the thermal and electrical insulation of the interspace of their modules is an important factor to determine the output power of the nTEGs. A new module structure using insulator/vacuum hybrid insulation with its design methodology that maximizes the output power is developed. Output power of a few milliwatts can be achieved by a wrist-band style mounting of the nTEG module with an optimized design.

1. Introduction

Internet of humans (IoH) is a new system for health and medical care using accumulated vital/medical data of humans, which enables us to give useful/important knowledges for improving/maintaining quality of life. Wearable devices play an essential role as a man-machine interface for IoH systems, and micro/nano thermoelectric generators (µ/nTEGs) [1, 2] can be applied to a power source of these wearable devices. The wearable devices for IoH postulate the following performances and features: (i) the devices need power of a few mW for short-distance wireless communication, since they are expected to be used with communication devices/facilities such as a smartphone or wireless LAN. (ii) A driving voltage of 0.5-1 V also needs to drive CMOS circuits in the wearable devices. (iii) A thin-film thermoelectric material is required for size/weight saving and cost reduction, which also gives rise to the usage of a micro- or nano-fabricated thermopile for µ/nTEGs. It is worthy to note that fabrication process technologies used for very-large-scale integrated circuits (VLSIs), such as lithography, can be diverted to µ/nTEGs fabrication, and these technologies highly enhances the degree of freedom of design for µ/nTEGs [2]. Also note that sophisticated minute-contact technologies used for VLSIs are also useful for forming thermal and electrical contacts of µ/nTEGs.

Recently, we proposed a transverse-type µTEG with highly integrated thin-film Seebeck elements and developed its design methodology [2]. Since the heat flow through the Seebeck elements are horizontal to the cold and hot plates of the module, high output power adaptable to wearable devices can be generated even by means of a thin-film thermopile. The thermal insulation of the interspace between the cold and hot plates of the module is one of the important factors to determine the output power, and thus the performance limits of the module can be obtained using the vacuum isolation [2].

In this paper, design methodology of transverse-type thin-film nTEGs with various module structures is developed and their performances are computationally analyzed. Although the thermal-electrical insulator of the interspace of the module severely degrades the performance, a newly proposed module structure using insulator/vacuum hybrid insulation that would be preferable to the device fabrication can achieve sufficient output power applicable to wearable devices.
2. Module structures and design methodology

Figs. 1 (a)-(c) show schematics of various transverse-type nTEG modules. The Seebeck elements occupy the $D \times L$ region on the inside of the $D \times D$ module area for all the modules. The interspace between the hot and cold plates in the $D \times L$ region is thermally and electrically insulated by vacuum (V) isolation (Fig. 1 (a)) or porous silica (PS) filling (Figs. 1 (b) and (c)), and its outside region of the module is insulated by V isolation (Figs. 1 (a) and (c)) or PS filling (Fig. 1 (b)). Hereafter, these insulation structures shown in Figs. 1 (a), (b) and (c) are simply denoted by V/V, PS/PS and PS/V, respectively.

Fig. 2 shows a homeothermic human model used for module design. The model includes heat flow limitation due to the thermogenic action of humans. In this system model, the maximum heat flow depends on the thermal resistance $K_M$ of the module and $K_{air}$ that is a sum of the thermal resistance $K_{air}$ from the module surface to ambient and the thermal resistance $K_{sh}$ of human skin near the skin. Therefore, these ($K_{air}$ and $K_M$) are optimized to achieve maximized output power under the homeothermic human model. In this paper, a maximum heat flow of $Q = 10 \text{ mW/cm}^2$ is assumed [3].

To maximize output power, the electrical resistance $R_M$ of the module and $K_M$ that are in the trade-off relation need to be optimized. For this purpose, a single trade-off parameter $\gamma$ ($0<\gamma<1$) that represents a ratio of the width $\gamma d$ of a thermoelectric element to the unit area width $d$ (see Fig.1) is introduced. The number and size of the thermoelectric elements and the resulting output voltage and power can be completely determined by $\gamma$ instead of the thermal and electrical resistances [2]. The important design parameters are the width $\gamma d$, the length $L$, the number $m_0$ of pair of the Seebeck element and the thickness $t_C$ of the contact metal layer, and the useful design indices are the electromotive force $V_S$ of each Seebeck element, the temperature difference $\Delta T$ of each Seebeck element, $K_M$, $K_{air}$ and $R_M$. The physical constants used for the following designs are shown in Table 1. Thermal and electrical resistance network models are used to analyse the output characteristics of the nTEGs. Thermal resistance due to radiation heat and spreading thermal resistance are used for the V and PS insulation portions, respectively. The output power on electrical matched load, given by $P_{out} = \frac{V_S^2}{4R_M} = \frac{(m_0V_S)^2}{4R_M}$, is used for the module designs, in which $V_S = \frac{m_0V_S}{2}$ represents the total electromotive force of the module.

Table 1. Physical constants used for module design.

| Module size $D \times D$ | Physical constants |
|-------------------------|--------------------|
| 1 cm$\times$1 cm        |                     |

| Thermoelectric material (BiTe) | Thickness $t_0$ | Seebeck coefficient $S = S_p - S_n$ | Thermal conductivity $\lambda = (\rho(\lambda + \rho_S)/2$ | Electrical resistivity $\rho = (\rho_{n\rho_S})/2$ |
|------------------------------|-----------------|-------------------------------|---------------------------------|-------------------------------|
|                              | 100 nm          | 434 $\mu$V/K                  | 1.43 W/(m$^2$K)                | 8.11 $\mu$Ωm                 |

| Temperature difference $\Delta T$ | 10 K |
|-----------------------------------|------|
| Interconnect/contact material (Cu) | $\lambda_{Cu}$ = 386 W/(m$^2$K) | $R_{Cu}$ = 17 $n$Ωm |
| Interlayer insulator (Porous Silica) | $\lambda_{PS}$ = 35.7 mW/(m$^2$K) |

Fig. 1. Schematics of transverse-type nTEGs using (a) V/V, (b) PS/PS and (c) PS/V modules.

Fig. 2. Homeothermic human model of a human body/wearable device/ambient system.

Fig. 3. $P_{out}$ and design parameters/indices as a function of $\gamma$ for the V/V insulation module.
Fig. 4. $P_{\text{out}}$ and design parameters/indices as a function of (a) $t_c$, (b) $L$ and (c) $m_0$ for the V/V module, in which all the parameters/indices are optimized by $\gamma$. $t_c$ is set to $t_c = (1+\gamma)d$ for (b) and (c).

Fig. 5. $P_{\text{out}}$ and design parameters/indices as a function of (a) $t_c$, (b) $L$ and (c) $m_0$ for the PS/PS module, in which all the parameters/indices are optimized by $\gamma$.

Fig. 6. $P_{\text{out}}$ and design parameters/indices as a function of (a) $t_c$, (b) $L$ and (c) $m_0$ for the PS/V module, in which all the parameters/indices are optimized by $\gamma$. $t_c$ is set to $t_c = (1+\gamma)d$ for (b) and (c).

3. Design and performance

Firstly, the optimum design and resulting performance of the V/V module that gives the performance limit of the nTEGs are discussed. Fig. 3 shows $P_{\text{out}}$, $v_S$, $\Delta T$, $\beta \Delta T$, $\gamma d$, $K_M$, and $R_M$ as a function of $\gamma$, in which $t_c$, $L$, $m_0$, and $K_M'$ are fixed for simplicity ($K_{M'}$ is adjusted to a particular value so that $Q$ reaches 10 mW at the $P_{\text{out}}$ peak). $K_M$ and $R_M$ increase with increasing $\gamma$ owing to the increase in $\gamma d$, and $P_{\text{out}}$ shows the peak shape. Therefore, $P_{\text{out}}$ is optimized by the single parameter $\gamma$. The $\gamma$ value at the peak position represents the optimum condition of $K_M$ and $R_M$.

Fig. 4 (a) shows $P_{\text{out}}$ and the other design parameters/indices as a function of $t_c$ for the V/V module. $P_{\text{out}}$ is almost independent of $t_c$ and remains constant at a maximized high value (~28 $\mu$W). Although $v_S$ is maintained constant and $m_0$ decreases with increasing $t_c$, i.e., the total electromotive force $V_S$ decreases with increasing $t_c$, $R_M$ can be reduced (or designed) so that $P_{\text{out}}$ is kept constant. The constant $v_S$ can be achieved by the constant $\beta \Delta T$ (or $K_M$). Note that $m_0$ (which is a determination factor of $V_S$) can decreases with increasing $L$ (which determines $R_M$) with $K_M$ kept constant so that $P_{\text{out}}$ remains constant at the highest value. Figs. 4 (b) and (c) show $P_{\text{out}}$ and the other design parameters/indices as a function of $L$ and $m_0$, respectively, for the V/V module. In both the cases, $P_{\text{out}}$ also remains constant at 28 $\mu$W, since $v_S$ is almost unchanged and the correlation between $m_0$ and $L$ (or $R_M$) is substantively the same as the case in Fig. 4 (a). The maximized $P_{\text{out}}$ value can be achieved by a number of combinations of $L$ and $m_0$, and $\gamma d$ is determined by a selected $m_0$ (or $L$) value. The wide $\gamma d$ range between a few hundreds of nanometers to a few micrometers is applicable for the V/V module.
design.

The PS/PS module is preferable from the point of view of device fabrication. However, the output power is severely degraded. Fig. 5 (a) shows $P_{\text{out}}$ and the other design parameters/indices as a function of $I_{C}$ for the PS/PS module. $P_{\text{out}}$ exhibits a single peak shape that results from the $I_{C}$-dependence on $V_{S}$, $m_{0}$, and $R_{M}$. Figs. 5 (b) and (c) show $P_{\text{out}}$ and the other design parameters/indices as a function of $L$ and $m_{0}$, respectively, for the PS/PS module. In both the cases, $P_{\text{out}}$ achieves a peak. The maximum $P_{\text{out}}$ value is severely lowered in comparison with the case of the V/V module. The PS/PS module requires the contact metal layer with thicker $I_{C}$ in order to achieve a $K_{M}$ value comparable to that of the V/V module. This is due to the high thermal conductivity of the PS insulation. In this situation, $m_{0}$ of the PS/PS module is smaller than that of the V/V module, and $L$ ($R_{M}$) of the PS/PS module is reduced (enlarged) in comparison with the case of the V/V module. Therefore, $P_{\text{out}}$ is degraded for the PS/PS module.

The PS/V module that would be relatively easy-to-fabricate insulation structure is effective at improving output characteristics of nTEGs. Fig. 6 (a) shows $P_{\text{out}}$ and the other design parameters/indices as a function of $I_{C}$ for the PS/V module. $P_{\text{out}}$ is enhanced when the contact metal layer with thinner $I_{C}$ is used. This is because $V_{S}$ and $m_{0}$, i.e., $V_{S}$, can effectively increase with decreasing $I_{C}$, compared with the increase in $R_{M}$. Note that although $m_{0}$ decreases with increasing $L$ so that $K_{M}$ is kept constant, $\beta \Delta T$ ($V_{S}$) drops with increasing $I_{C}$ owing to the effect of the parasitic thermal resistance of the metal contacts. Fig. 6 (b) shows $P_{\text{out}}$ and the other design parameters/indices as a function of $L$ for the PS/V module. $P_{\text{out}}$ is strongly enhanced by reducing $L$. Owing to the correlation between $m_{0}$ and $L$, $m_{0}$ increases with decreasing $L$ so that $K_{M}$ is almost kept constant, although $K_{M}$ drops for wider $L$ values. Therefore, $V_{S}$ and $V_{S}$ are enhanced by reducing $L$, resulting in the increase in $P_{\text{out}}$. Fig. 6 (c) shows $P_{\text{out}}$ and the other design parameters/indices as a function of $m_{0}$ for the PS/V module. $L$ decreases with increasing $m_{0}$ with $K_{M}$ held constant owing to the correlation between these parameters. In this case, $V_{S}$ is successfully maintained constant. Therefore, $V_{S}$ and thus $P_{\text{out}}$ are enhanced with increasing $m_{0}$. Note that $R_{M}$ increases with $P_{\text{out}}$ and overhigh $R_{M}$ suppresses the enhancement of $P_{\text{out}}$, as shown in Figs. 6 (a)-(c). It is worthy to note that the optimum feature size of the Seebeck elements is in 20-80 nm as shown in Fig. 6, i.e., the “nano” TEG structure is required for this module.

Fig. 7 (a) shows $P_{\text{out}}$, $Q$ and $K_{M}$ as a function of $K_{M}'$ for the PS/V module, in which no restrictions are imposed on $Q$. $P_{\text{out}}$ decreases with increasing $K_{M}'$. $K_{M}'$ needs to be selected within the heat flow limit of humans. An alumite-treated fine-fin plate structure would allow $K_{M}' \approx 700$ K/W cm$^{-2}$, and thus $P_{\text{out}} > 20 \mu$W/cm$^{-2}$ can be achieved. This $K_{M}'$ value also adapts the thermogenic ability of humans at room temperature. Fig. 7 (b) shows output characteristics of the PS/V insulation module, in which an optimum design at $L=10$ μm shown in Figs. 6 (b) and (c) is used and the module-mounting area is varied from 20 to 120 cm$^{2}$. When the module is mounted to a wrist-band style (100 cm$^{2}$), $P_{\text{out}}$ of 1.6 mW can be achieved. This output value is sufficiently applicable to wearable devices with short-distance communication functionality.

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