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Flexible thermoelectric power generator with Y-type structure using electrochemical deposition process

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HIGHLIGHTS

- A novel idea of lateral Y-type thermoelectric cells is proposed.
- A new fabrication process for flexible microstructure is performed.
- The state-of-art design, modeling for thermoelectric generators are researched.
- High output power density harvested from human body temperature has been achieved.

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ABSTRACT

The harvest of thermal energy using the thermoelectric (TE) effect is one of the potential methods for body area network power sources. This paper demonstrates a new approach of an electrochemical deposition process to fabricate self-endurance flexible thermoelectric generators (FTEGs). A novel idea of lateral Y-type TE cells instead of conventional vertical π-type cells is proposed to enhance the performance of the temperature harvest. On the other hand, the thick films of thermoelectric materials (N type- bismuth telluride and P type- antimony telluride) are successfully synthesized. For the first time, the electrochemical deposition of thermoelectric materials is used to integrate thermoelectric materials with a flexible support, where a silicon substrate is used as a sacrificial material. With the temperature difference between the human body (approximately 37 °C) and ambient environment (15 °C) using natural convection, the device can generate approximately 3 $\mu W/cm^2$ of output power density.

1. Introduction

Body area network (BAN) is a promising technology for many applications in the residential and medical fields. The widespread implementation of BAN expects self-supplied power sources that are able to provide power for its entire lifespan. Devices that can scavenge energy from surroundings, therefore, are being researched for this purpose. The development of thermoelectric power generators (TEGs) has merited much attention due to its capability to convert low-grade waste heat into electrical energy using the Seebeck effect. Many efforts have been investigated in this field to date [1–18]. To enhance the performance of TEGs, thermoelectric material syntheses and design optimizations are key factors. Among thermoelectric materials, N-type bismuth telluride (Bi_2Te_3) and P-Type antimony telluride (Sb_2Te_3) are widely used due to their highest performances for applications near room temperature [7,19]. The conventional vertical π-type structure of Solid Thermoelectric Generators (STEGs) has been reported in Refs. [4,8,9]. Because the temperature difference is governed by the pass-length of the heat flow, the vertical π-type structure needs ultra-thick films of thermoelectric material to improve its performance. However, the synthesis of thick thermoelectric materials in micro devices remains a challenge. To overcome this drawback, thermocouples (TCs) are considered to be laid laterally rather than in a vertical position. In general, this structure consists of a series of TCs constructed laterally on a solid sustaining substrate [12,13]. Nevertheless, long TCs placed laterally on a thin membrane can improve the thermal yield capability, but they cannot harvest the temperature difference vertically via top and bottom surfaces of the device. Instead, heat sources need to be placed on the left and right ends. The structure of the conventional lateral type STEGs is shown in Fig. 1(a). This can cause great appeal for actual applications of thermal energy harvesters. To solve all of the obstacles, this work has proposed a novel design, modeling and fabrication of the lateral Y-type structure, which combines lateral TCs together

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Nomenclature

g_1	gaps between two neighboring TCs in series (μm)	U_L	generated potential on the load (mV)
g_2	gaps between two neighboring parallel TCs lines (μm)	R_L	load resistance (Ω)
W	width of TCs (μm)	P_L	generated power (μW)
L	length of TCs (μm)	α	Seebeck coefficient (μV/K)
t	thickness of TCs (μm)	α_n	absolute Seebeck coefficient of N-type thermoelectric materials (μV/K)
ρ_n	electrical resistivity of N-type thermoelectric materials (μΩ m)	α_p	absolute Seebeck coefficient of P-type thermoelectric materials (μV/K)
ρ_p	electrical resistivity of P-type thermoelectric materials (μΩ m)	S	cross-area (μm^2)
R_{in}	internal electrical resistance (Ω)		
ΔT	temperature difference (°C)		
V_0	open circuit voltage (mV)		

with vertical heat guide columns. The Y-type structure of TCs sandwiched between two thick polymer layers with low thermal conductivity can reduce the heat loss in the vertical direction. Hence, the temperature difference into the lateral direction can be attained, and much more thermal energy is scavenged than in the conventional vertical π-type structure with a limited thickness of thermoelectric films.

Another obstacle that needs to be solved is the fabrication process. It is necessary to remove the top and bottom sustaining solid substrates by the self-endurance structure for FTEGs. Many previous works have reported that STEGs with electroplated materials can be completed by a two-substrate method [11,20–22]. Herein, N-type and P-type thermoelectric materials are deposited separately on two different substrates. A single substrate with an individual material would be joined with each other at the end of the process. Another approach for STEGs fabrication is to deposit both N-type and P-type thermoelectric materials on the same substrate [7–10]. The advantage of this method is that electrical contacts can be grown by the electroplating deposition or boding materials. However, this method encounters another problem. Since TCs are deposited on a metal seed layer, an electrical short circuit in the TCs is caused if the seed layer is not removed. The laser cutting method in Ref. [4] has solved this behavior. Nevertheless, these methods can be only applied to solid membrane substrates. Hence, the fabrication of FTEGs based on sputtered or evaporated thermoelectric materials upon a flexible substrate is still a widely used method [5,6]. These research efforts suffer not only the disadvantage of the high internal electrical resistance but also the performance of the temperature harvest is low due to a thin thickness of the thermoelectric materials. That is the reason why all the best FTPGs to date are based on a print-screening method, which shows the possibility to synthesize thick thermoelectric films [1,10]. However, the print-screening method has the disadvantage of the low integration of TCs.

To solve the above issues, for the first time, the electrochemical deposition is used to integrate the thermoelectric materials inside self-endurance flexible structures, where the silicon substrate is used as a sacrificed material. In addition, the synthesis of thermoelectric materials including Bi_2Te_3 and Sb_2Te_3 performed by the electrochemical deposition method allows achieving thick films and reducing the internal electrical resistance [23]. The detailed structure of the proposed device is sketched in Fig. 1(b). Basically, it consists of N type-bismuth telluride and P type-antimony telluride, which are deposited laterally on the membrane. Heat is guided to the TCs via copper thermal guides, which are designed to lead the heat flux vertically from bottom to top sides of the device. PDMS (Polydimethylsiloxane) is used as a base material of the flexible power generator because of its good flexibility and low thermal conductivity (0.15 W/m K [24]). Metallic barrier contacts are employed to lessen the internal electrical resistance. Herein, multilayers of the metallic contact of Ti-TiN-Au-Cu are formed between TCs and heat guides. When a temperature difference is applied between the top and the bottom surfaces, heat will vertically conduct through the heat guides. The temperature difference harvested using the Seebeck effect is, in essence, to generate the electricity.

2. Design and FEM (Finite Element Method) simulation

Fig. 2(a) and (b) show the top view of the proposed FTEGs and the cross-section structure of the relevant selected area, respectively. The device consists of TCs connected electrically in series, forming a module with a geometric area of $1 \times 1\ cm^2$. W and L are the width and length of TCs, respectively. The length of heat guides is g_1 (∼600 μm). The gap g_2 between two neighboring parallel TCs lines is approximately 900 μm.

The equivalent circuit of the fabricated thermoelectric generator as a power source with a load resistance is shown in Fig. 3. The generated power P_L is given by

$$P_L = U_L I_L = \frac{U_L^2}{R_L} = \frac{\left[\frac{V_0 R_L}{(R_{in}+R_L)}\right]^2}{R_L}, \quad (1)$$

where I_L is the electrical current flowing in the load, V_0 is the open circuit voltage, U_L is the generated potential on the load, R_{in} is the total internal electrical resistance of the device which mainly depends on the dimension and electrical resistivity of TCs. When the load resistance R_L is equal to the internal electrical resistance R_{in} (matched load condition), following maximum output power is obtained

$$P_{Lmax} = \frac{(V_o)^2}{4R_{in}}. \quad (2)$$

The open circuit voltage V_0 produced by the Seebeck effect is defined as

$$V_0 = n(\alpha_n + \alpha_p)\Delta T, \quad (3)$$

where n is the number of TCs pairs integrated into the device, ΔT is the temperature difference harvested by each TC, α_n and α_p are the absolute Seebeck coefficients of N-type and P-type thermoelectric materials, respectively.

Therefore, the maximum output power can be calculated as

$$P_{Lmax} = \frac{(V_o)^2}{4R_{in}} = \frac{[n(\alpha_n + \alpha_p)\Delta T]^2}{4n\left(\rho_n \frac{L}{S} + \rho_p \frac{L}{S}\right)}, \quad (4)$$

where L is the length, S is the cross-area of each TCs, ρ_n and ρ_p are electrical resistivities of N-type and P-type thermoelectric materi-

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