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Fabrication of flexible thermopile generator sheet

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Abstract

In this study, a flexible thermoelectric power generator has been proposed. The proposed thermoelectric power generator is composed of a polyimide sheet, a Ni-Cu thermopile on the polyimide sheet, and heat sink and heat absorber sheets. The prototyped thermoelectric power generator has 66mm-length, 48mm-width and 2.5mm-height. As a result of characteristic evaluation, open-circuit voltage of 16μV/K per thermocouple was obtained. A prospect for practical application of the thermoelectric power generator for curved surface was confirmed.

Keywords : flexible structure, thermoelectricity, thermopile, Seebeck effect, power generation

1 INTRODUCTION

Human beings can only use limited part of the available energy, despite natural or artificial power generations. Remaining part of the energy is wasted into the atmosphere as heat energy. Therefore, the effective utilization of enormous waste energy is an important issue from the point of view about the earth environment. For example, suppose a co-generation system is based on gas turbine combustion, the heat drop between the maximum combustion temperature and exhaust temperature is used for power generation with the state of the art efficiency available today. But, temperature below the exhaust gas may be wasted. Although thermoelectric power generation has relatively low energy conversion, it may be compatible to use above mentioned waste energy for power generation. It also has benefit of wide application fields, due to maintenance-free and possibility of wearable power generation by human body.

However, major research on thermoelectric power generator is to develop the thermoelectric materials. Therefore, the research on the structure is limited. Most of the conventional thermoelectric power generators have the structure which consists of a rigid heat sink plate, a rigid heat absorber plate and a thermopile. The two rigid plates are parallel to each other and the thermopile is sandwiched between them [1]. Therefore, these kinds of thermoelectric power generators are only possible to apply on the flat surface, and application fields are limited.

In this study, a flexible thermoelectric power generator sheet has been proposed [2]. The structure of the thermoelectric materials is fabricated by the photolithography, and has advantages for integration and miniaturization. To realize flexibility of thermopile generator sheet, the wavy and slit structure is adopted. Hereafter, this thermoelectric power generator is called a flexible thermopile generator with slit (FTGS). If FTGS is attached to curved surface of heat source, it can have larger attachment area. So FTGS will gain more heat energy from heat source than conventional thermopile generator. The prototyped FTGS has 66mm-length, 48mm-width and 2.5mm-height. In this study, structure, fabrication process and characteristic evaluation of the FTGS are reported. A result of characteristic evaluation gives more excellent power generation and mechanical properties than previous study [2,3].

2 STRUCTURE

Schematic of the FTGS is shown in Fig.1. Thermocouples are connected in series on a polyimide sheet. The polyimide sheet is called a thermopile sheet. Thermoelectric materials are Ni and Cu. Hot and cold junctions are formed by bending the thermopile sheet to wavy form. Finally, the FTGS is completed by setting the wavy thermopile sheet between the flexible heat sink and absorber sheets. The hot and cold junctions are obviously reversible. Because of the wavy thermopile with slits, FTGS can bend around two orthogonal axes.

Dimensions of the thermocouple are shown in Fig.3. Ni-Cu thermocouples were fabricated on the slopes of the wavy polyimide sheet. The wavy form of Ni junction was formed to increase contact length and to prevent electrical disconnection during bending process (Fig.2).
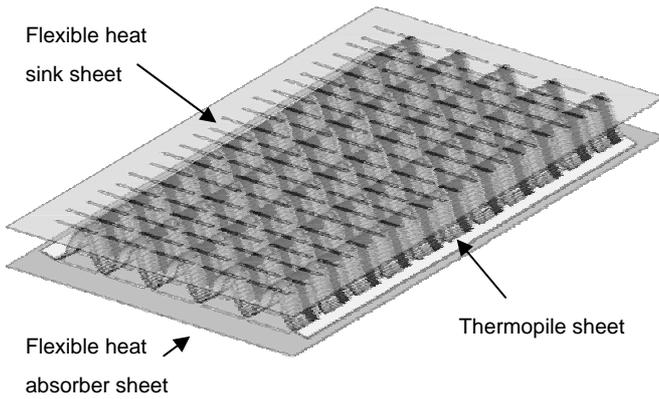
Figure 1. Schematic of flexible thermopile generator with slit structure.
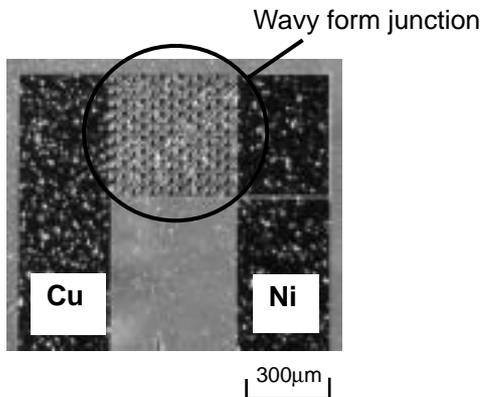
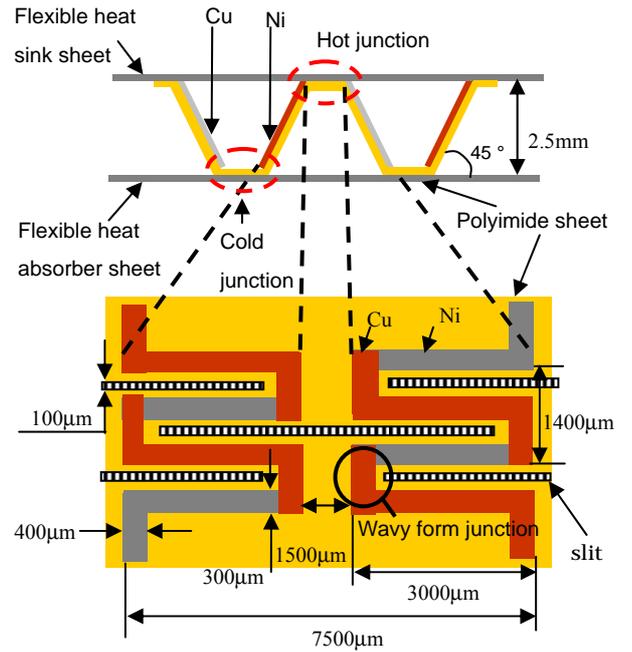Figure 2. Ni-wavy junction to increase the contact area between Ni and Cu.

Figure 3. Cross sectional area and development figure of thermopile power generation sheet.

3 DESIGN

Suppose simple and ideal n thermocouples connected in series, *Seebeck* output voltage is given as [3]

$$V = n\alpha_{AB}(T_H - T_C) \qquad (T_H > T_C) \tag{1}$$

where α_{AB} denotes the relative *Seebeck* coefficient of material A and B, which compose thermopile. T_H and T_C are temperatures of hot and cold junctions, respectively. If external load r equal to inertial load of FTGS is connected, the maximum output power is given as [4],

$$P_{MAX} = \frac{n^2\alpha_{AB}^2(T_H - T_C)^2}{4r}. \tag{2}$$

The figure of merit Z, which denotes the performance of thermoelectric power generation by thermocouple is given as [3, 4],

$$Z = \frac{\alpha_{AB}^2}{\left(\sqrt{\kappa_A\rho_A} + \sqrt{\kappa_B\rho_B}\right)} \tag{3}$$

where κ_A, κ_B, ρ_A and ρ_B are thermal conductivity and resistivity of materials A and B, respectively.

A combination of Ni and Cu is used for prototyped thermocouple. The V and P_{MAX} can be calculated by Eqs.(1) and (2), respectively. In the calculation, T_H=308K, T_C=307K and n=1 are used. The results are shown in Table 1. Table 2 shows parameters used for the calculations.

Table 1. Calculated value of V and P_{MAX} per thermocouple.

V[μV/K]	P_{MAX}[pW/K]
20.6	12.3

Table 2. Parameters used for calculations.

Materials	α_{AB}[μV/K]	Z[10⁻⁶/K]	r[ ]
Ni and Cu	20.6	17.0	8.62

Heat conduction inside the FTGS may depend on the structure, and it is difficult to obtain closed form solution of temperature distribution for specific structure. Therefore, FEM analysis of heat conduction for the FTGS was carried out to estimate the temperature difference between the hot and cold junctions. As a boundary condition, temperature difference between the heat absorber and sink sheets is fixed at 1K. Fig.4 shows a result of FEM analysis. The resultant temperature difference between the junctions is 0.91K. By using FEM result, the output voltage of the FTGS should be modified from Eq.(1) as,

$$V_{FTGS} = 0.91 n\alpha_{AB}(T_H - T_C). \qquad (5)$$

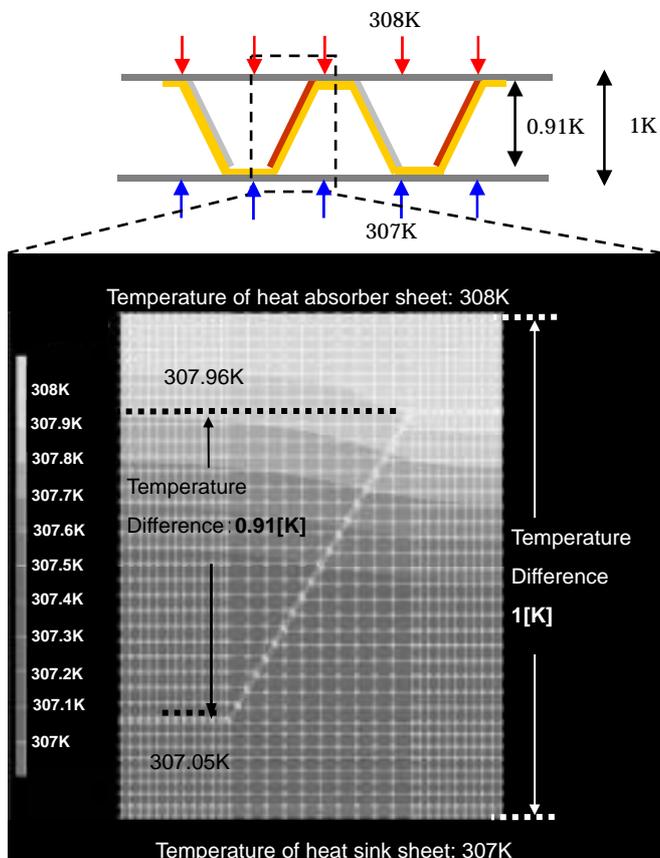

Figure 4. Schematic view of FEM analysis.

4 FABRICATION PROCESS

The thermocouples were formed on the polyimide sheet by the lift-off process. AZ5214E photo resist was selected for this process. AZ5214E is easy to form inverse tapered cross section suitable for the lift-off process [2].

The slits of thermopile sheet and heat sink and absorber sheet were fabricated by excimer laser direct writing process. Cu film deposited on polyimide film is used for the heat sink and absorber sheets in order to increase performance of heat conductivity.

The thermopile sheet was formed into wavy form with the use of a holding fixture having vacuum chuck on top of the wavy structure (Fig.5). After holding the thermopile sheet on the wavy structure, the heat sink and absorber sheets were bonded onto the thermopile sheet to form the FTGS (Fig.6). Finally, connector was attached to supply power to the external devices easily.
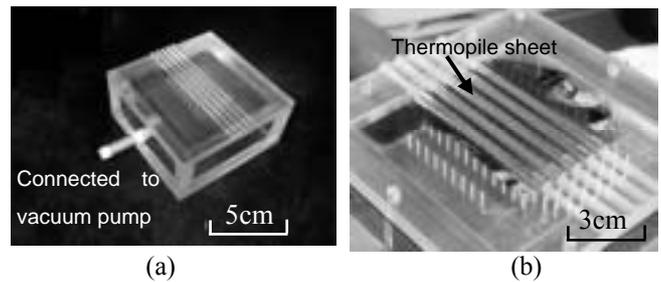

Figure 5. Fixture for holding wavy configuration (a), and thermopile sheet kept into wavy form by the fixture (b).
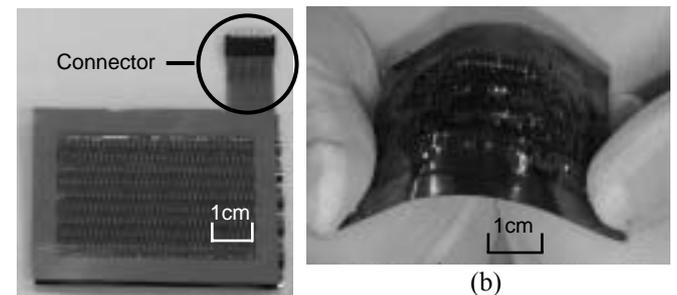

Figure 6. Schematic of FTGS (a), and demonstration of bending of FTGS by hand.

5 EXPERIMENT

In order to measure the performance of the power generation, FTGS having 38 thermocouples was placed on a temperature control device with the Peltier element [5]. It was used to keep arbitrary temperatures between heat absorber sheet (T_H) and heat sink sheet (T_C). The output voltages were measured with the variation of temperature difference ($\Delta T = T_H - T_C$). Fig.7 shows the relation between ΔT and the output voltage. An average of the output voltage was 16μV/K per thermocouple. The V_{FTGS} predicted by FEM is 18.7μV/K, and 120% of the experimental value of 16μV/K. Therefore, the result of FEM analysis is reasonably agreement with the experiment.
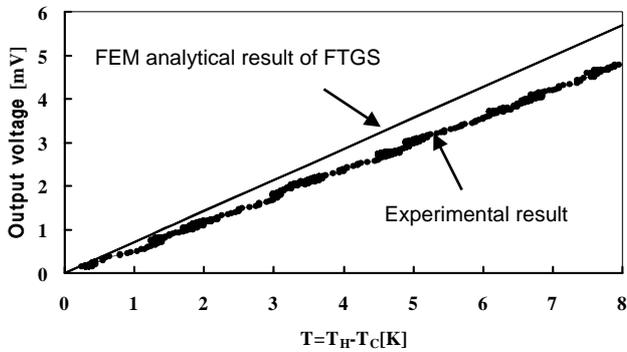

Figure 7. Relation between $\Delta T = T_H - T_C$ and output voltage (38 thermocouples).

The minimum bending curvature, with which the FTGS can maintain its performance without any damage, has been investigated. Table 3 shows the relation between radius of curvatures of the typical parts of the human body and electric resistance of the FTGS put on them. The FTGS does not break up to the radius of bending curvature of 9mm, and this corresponds to the typical radius of the cross section for thumb (see Table 3). The usefulness of the FTGS for wearable power generation has been confirmed.

6 CONCLUSION

As can be seen from the results in Fig.7, the experimental value was proximately 83% of the FEM analytical result. FTGS remains its performance until it is bended to radius of curvature of 9mm. The prototyped FTGS gave a prospect for practical application of thermopile generation with flexible structure. In the future, the structure of the FTGS will be optimized to realize complete in plane and out of plane bending deformation, and miniaturization and integration of

thermocouples on a polymer sheet. In order to achieve higher output voltage and power of FTGS, thermoelectric material of BiTe (P type and N type) will be adopted. Table 4 shows the predicted difference of power generation between Cu-Ni couple and BiTe thermocouple.

Table 3. Relation between radius of curvatures of typical parts of the human body and output voltages of FTGS.

Radius of curvature [mm]	∞	50	40	27.5	9
Typical parts of human body	Hand	Upper arm	Forearm	Wrist	Thumb
Electric resistance (38 thermocouples) [Ω]	594	594	602	599	606

Table 4. Difference of thermoelectric materials (per thermocouple and 1K).

Thermoelectric material	Relative *Seebeck* coefficient [μV/K]	Figure of merit Z [10^-6/K]	Electric Resistance [Ω]	Maximum output power [pW]
Cu-Ni	20.6	17	4.8	5.97
BiTe(P type and N type)	200	2500	292	34.2

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