Paper

Self-standing Polysilicon-metal Thermopile for Micro Power Generator

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ABSTRACT

A prototype self-standing polysilicon-metal junction thermopile has been developed. In order to realize ideal higher thermal isolation, a thermopile without a membrane and having self-standing structure is proposed. It is arbitrary to select the heat absorber or the substrate as a hot contact, i.e. the hot and cold contacts can be inverted. The thermocouple is composed of an n - type polysilicon and an Au junction. The thermopile was fabricated by MICS (Multi-user Integrated Chip Service: three polysilicon layer structure) organized by the Cooperative Research Committee for Standardization of Micromachines in IEE of Japan. Output characteristics were measured as a function of distance between the hot contact of the thermopile and the radiation source, in order to confirm performance of the proposed thermopile as an accessory micro power generator. Seebeck voltage of more than 6.2mV was obtained in the case of connecting ten thermocouples in series for typical human skin (307K) used as a radiation source.

Key words: self-standing, micro power generator, Seebeck effect, MICS

1 INTRODUCTION

Thermopiles are widely used as sensing elements for temperature and radiation sensors [1][2]. Besides this, thermopiles are expected to be used as thermoelectric power generators. Output characteristics of the thermopile depend on temperature differences between the hot and cold contacts, thermal isolation and *Seebeck* coefficients of the thermocouple materials [1][2]. In the conventional case, part of the absorbed heat from a radiation source transfers from the hot contacts to cold contacts through a thermopile and an insulated membrane under the thermopile. The occupied heat absorber area within the plane is reduced, because the heat absorber on the hot contacts is arranged on the same plane of the cold contact portion. As a consequence, thermoelectric efficiency is relatively lowered.

This study focuses on enhancement of the thermoelectric efficiency of a thermopile introducing a self-standing structure shown in Fig.1. Figure 1 shows the final goal of our study. The proposed structure has two advantages, (a) the absorbed heat transfers from hot contacts to cold contacts only through the thermopile and no heat transfer will occur between the hot and cold contacts except for this, (b) the heat absorber area can be increased up to the chip area. As a consequence, temperature difference between the hot and cold contacts approaches the ideal value. In this paper, design, fabrication and characteristics of the self-standing polysilicon-metal junction thermopile for an accessory micro power generator are reported.

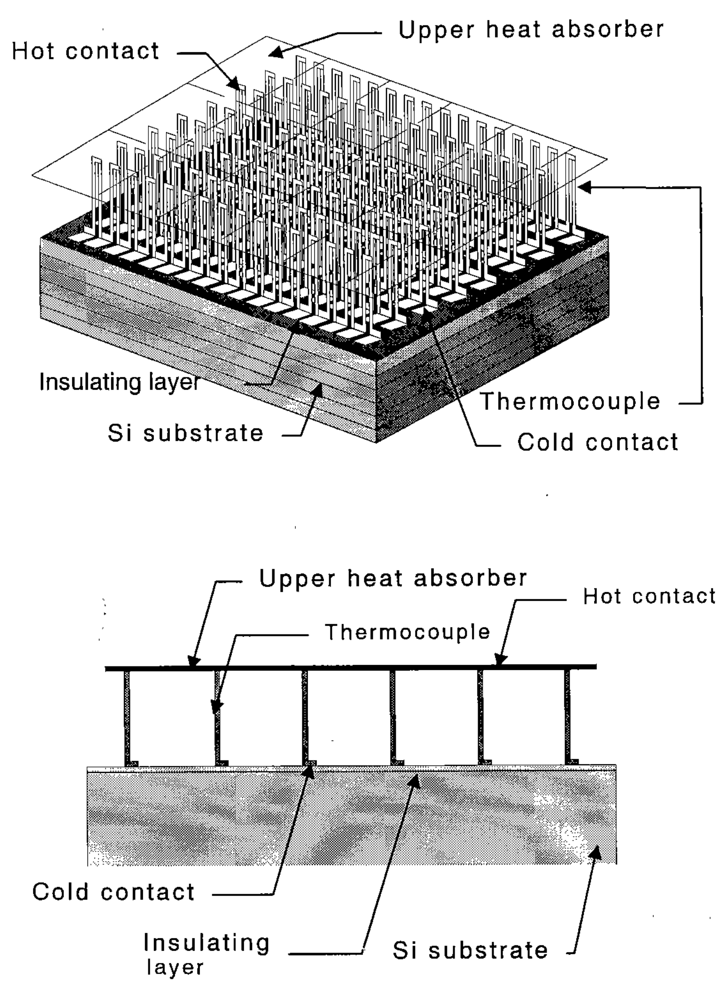


Figure 1. Schematic of self-standing thermopile.

2 DESIGN

The *Seebeck* voltage of the thermopile due to thermal radiation can be calculated from fundamental equations of thermal radiation, heat transfer and the *Seebeck* effect.

The fundamental equations used for the calculations are reviewed in [2] and [3].

Figure 2 shows a schematic of a thermocouple and corresponding heat energy balance. The thermocouple is composed of a heat absorber at the hot contact and thermoelectric legs. It is assumed that the temperature of the hot contact increases up to T_1 by absorbing a thermal energy P_{abs} at the heat absorber due to black body radiation, while the temperature of the cold contact remains at T_0. The thermal energy P_{abs} is decomposed into two components, one transmitted into the thermocouple P_{absT} and the other radiated from the heat absorber P_{absF}. It is also assumed that thermal convection and radiation from the thermoelectric legs can be neglected. Black body radiation is used to determine P_{abs} and given as

$$P_{abs} = \varepsilon E_b F A . \tag{1}$$

Where ε is the emissivity of the heat absorber, E_b is heat flux emitted from the black body surface, F is view factor and A is the heat absorber area, respectively. Then, the thermal energy balance equation can be described as

$$P_{abs} = P_{absT} + P_{absF} = \left(G_{th} + G_{radA}\right)\left(T_1 - T_0\right). \tag{2}$$

From equation (2), temperature difference between the hot and cold contacts of the thermocouple can be obtained as

$$T_1 - T_0 = \frac{P_{abs}}{G_{th} + G_{radA}} . \tag{3}$$

In equation (3), the thermal energy, thermal conductance of the thermoelectric legs G_{th} and thermal conductance due to radiation from the heat absorber G_{radA}, are defined as follows

$$G_{th} = \sum_i \frac{\kappa_i A_i}{L_i} . \tag{4}$$

$$G_{radA} = 4\left(\sum_i \varepsilon_i\right)\sigma_s T_1^3 A . \tag{5}$$

Where, κ_i, A_i, L_i and ε_i are thermal conductivity, cross section area, length and emissivity of the thermoelectric legs, respectively. σ_s and T are the *Stefan-Boltzmann* constant and the surface temperature of the heat absorber. Therefore, the *Seebeck* voltage of the thermopile (N thermocouples) can be described using the *Seebeck* coefficient α_i of the thermoelectric legs as

$$V_{OUT} = N\left(\alpha_1 - \alpha_2\right)\left(T_1 - T_2\right). \tag{6}$$

As can be seen from Eqs. (1) to (3), introducing a larger heat absorber area and removing insulator membrane obtains a larger temperature difference between the hot and cold contacts, namely, a larger *Seebeck* voltage. The proposed thermocouple structure shown in Fig.1 satisfies these conditions.

Figure 3 shows a schematic of the thermocouples, which compose the thermopile. Each thermocouple is composed of an n - type polysilicon layer and a Au/Cr composite layer. The Au/Cr composite layer can be used as a hinge in order to stand the thermocouple perpendicularly on the substrate. As shown in Fig.3, the thermocouple has self-standing bimorph structure. This structure might be deformed due to temperature variation. The thermocouple tips are expected to be firmly fixed on the heat absorber during the packaging. Therefore, it can be deduced that the deformation due to temperature variation can be negligible.

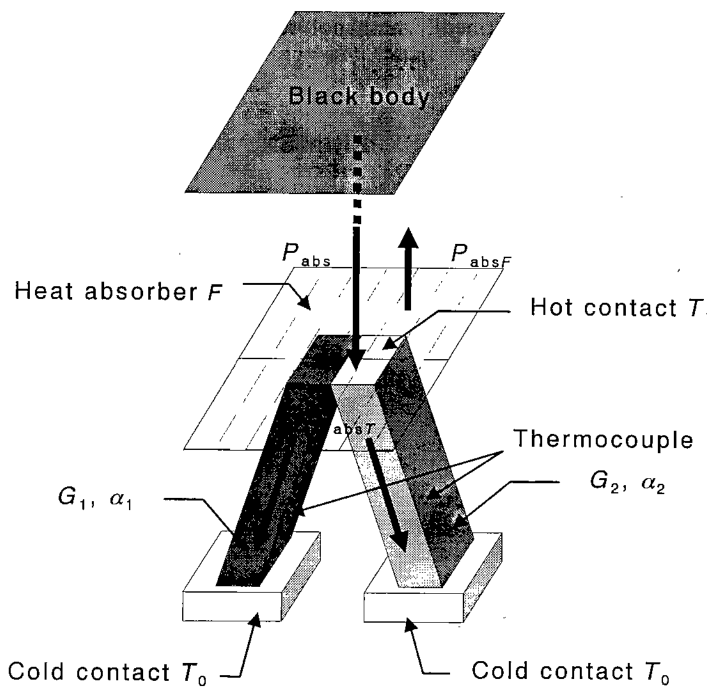


Figure 2. Thermal energy balance for thermocouple.

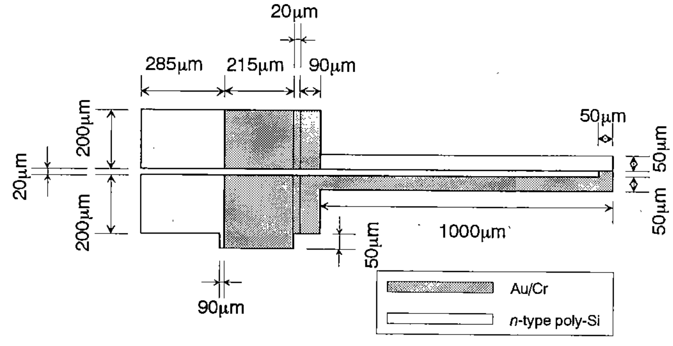


Figure 3. Dimension of thermocouple.

3 FABRICATION

The thermopile was fabricated by MICS (Multi-user Integrated Chip Service: three polysilicon layer structure) organized by the Cooperative Research Committee for Standardization of Micromachines in IEE of Japan [4] [5].

Figure 4 shows the fabrication process of the thermopile using MICS. The standard process of MICS is shown in steps (a) to (f). Users of this service perform the last step of release (g) after delivery from MICS. As shown in (g), the Au/Cr composite layer can be used as one of the thermoelectric legs and hinges in order to stand the thermopile perpendicularly on the substrate. The release was performed through the processes of HF wet etching, NH_4F rinsing, hydrophobic treatment, methanol rinsing, and baking in order.

4 EXPERIMENT

Figure 5 shows the SEM image of the prototype thermopile after releasing. The thermoelectric legs were bent as shown in the Figure. Vertical deflection of the hot contact tip from the substrate was approximately 240μm.

Seebeck voltage was measured in the case of connecting ten thermocouples in series. Fundamental characteristics of the thermopile without heat absorber were investigated for an accessory micro power generator using human skin as a radiation source. A black body plate having uniform temperature 307K was used as the radiation source. 307K corresponds to a typical human skin temperature [6].

The *Seebeck* voltage was measured as the function of vertical distance between the hot contact tip and the heat source as shown in Fig.6. Figure 8 shows the experimental results of the *Seebeck* voltage of the thermopile.

5 DISCUSSION

Theoretical *Seebeck* voltage can be obtained from Eqs.(1) to (6) as previously mentioned. Comparing the configureuration of Fig.6 to Fig.2, the thermocouple surface area acts as a heat absorber area A in place of the upper heat absorber. Therefore, emissivity ε, view factor F and heat absorber area of the thermopile A must be modified to be compatible for this problem.

The total emissivity ε can be obtained as a sum of the emissivity of each layer. In order to determine the view factor F between the heat source and the thermopile, the heat source and the thermopile can be approximated to two square surfaces, which are parallel to each other [7]. The heat absorber area A corresponds to the surface area of the thermopile, contributing to the heat absorption and the radiation. Figure 7(a) shows the schematic structure of the thermopile that is composed of an n - type polysilicon layer and a Au/Cr composite layer. Figure 7(b) shows an equivalent circuit to determine the *Seebeck* voltage.

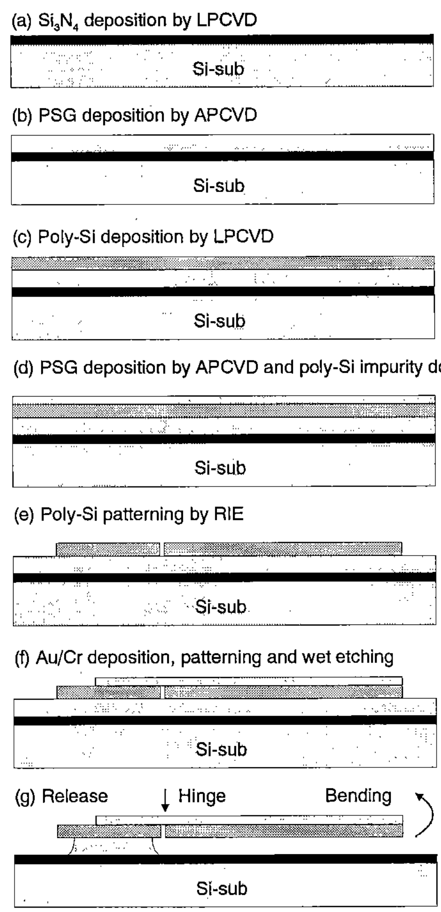


Figure 4. Fabrication process of thermopile by MICS [4][5].

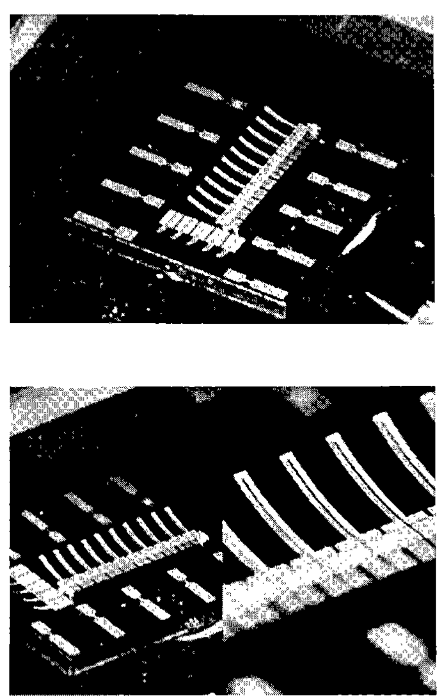


Figure 5. Photographs of thermopile after releasing.

According to the circuit, the n - type polysilicon layer and the Au layer must be taken into account in order to determine the *Seebeck* voltage [8] ref.

Following these assumptions and Eqs.(1) to (6), theoretical output voltage is calculated as shown in Fig.8. Material properties used for the calculation are sheeted in Table1. The experimental results are in reasonable agreement with the theoretical calculation.

In the case of an electrical resistance of the load is equal to the resistance of generator, the electrical power P_{out} is given by [9].

$$P_{OUT} = \frac{IV_{OUT}}{2} = \frac{V_{OUT}^2}{4R} \qquad (7)$$

Where V_{OUT} is the output voltage, I is the electrical current, and R is the electrical resistance of the thermopile. The electrical resistance of the thermopile can be calculated from the geometry in Fig.3 and the resistivity in Table1. The calculated value is 5.42kΩ and very close to the experimental value of 5.50kΩ. Based on equation (7) and the experimental output voltage in Fig.8, the maximum electrical power of 3μW is obtained at the distance between the hot contact and the heat source is 1mm.

6 CONCLUSIONS

In order to realize ideal higher thermal isolation, a thermopile without a membrane and having a self-standing structure has been proposed. In this paper, design, fabrication and experiment on a prototype self-standing polysilicon-metal junction thermopile were described. The thermocouple was composed of an n - type polysilicon and a Au junction. A prototype thermopile was fabricated by MICS.

In order to confirm performance of the thermopile, the output voltages were compared with theoretical values. Outputs were measured as a function of distance between the hot contact of the thermopile and the heat source. The temperature of the heat source was maintained at 307K, corresponding to typical human skin temperature. Seebeck voltage of more than 6.2mV was obtained in the case of connecting ten thermocouples in series for typical human skin (307K) used as a radiation source. The prospect for application of the thermopile into an accessory micro power generator has been obtained.

In future work, a thermopile with an upper heat absorber will be fabricated and characterized.

Table1. Material properties used for calculations.

	n -type polysilicon	Si_3N_4	Cr	Au
Thermal conductivity κ [W/m^2]	29.0	20.0	90.3	315.0
Resistivity ρ [Ωcm]	$1.1 \times 10^{-3*}$	-	1.31×10^{-5}	2.25×10^{-6}
Emissivity ε (307K)	0.30	-	4.6×10^{-2}	1.9×10^{-2}
Zeebeck coefficient α [μV/K]	-110	-	17.3	7.9

*...Sheet resistance 29 Ω/square

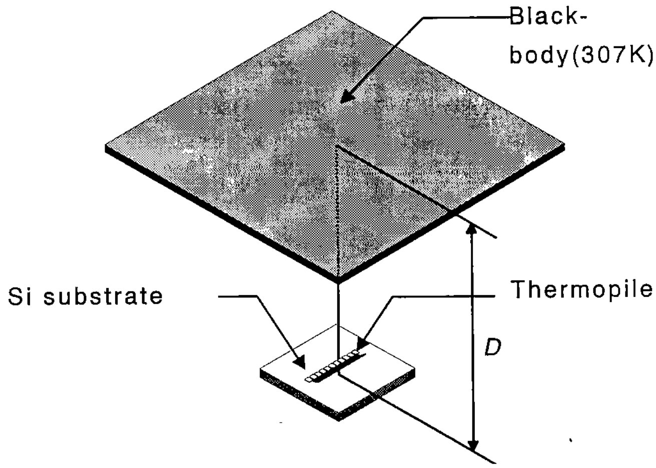
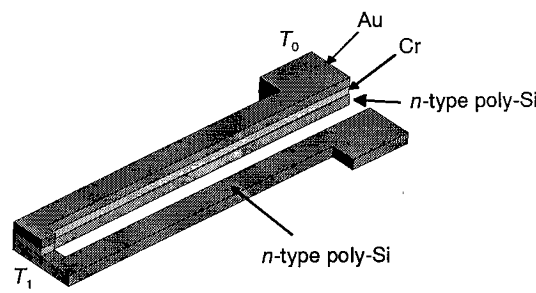
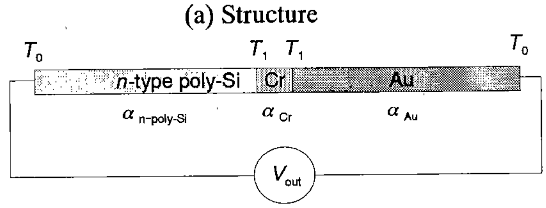


Figure 6. Experimental configuration.



(a) Structure



$$V_{out} = \alpha_{n\text{-poly-Si}}(T_0 - T_1) + \alpha_{Cr}(T_1 - T_1) + \alpha_{Au}(T_1 - T_0)$$

$$\doteq (\alpha_{Au} - \alpha_{n\text{-poly-Si}})(T_1 - T_0)$$

(b) Equivalent circuit

Figure 7. Equivalent thermocouple circuit for determination of Seebeck voltage [8].

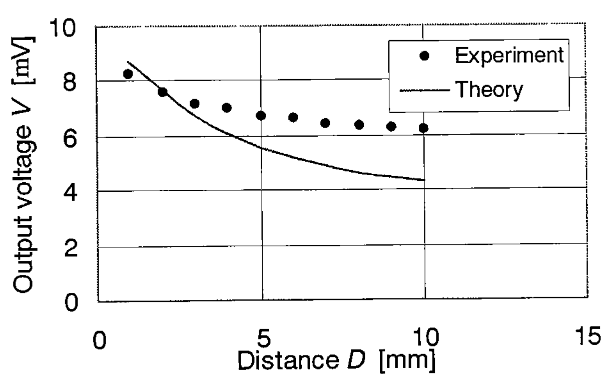


Figure 8. Seebeck voltage of thermopile (N=10).

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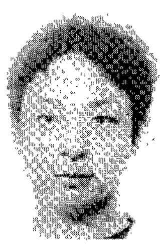

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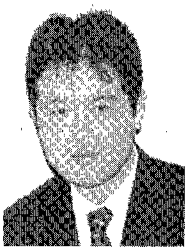

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