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A plate-type thermoelectric power generator with an oxidized bi-metal interface for power generation from a small temperature difference

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ABSTRACT

A plate-type thermoelectric power generator was fabricated from an Fe plate. The Fe plate was initially oxidized. Next, an Al layer was deposited on the plate, which had been partially covered with an SiO_2 layer for electrical insulation, and a bi-metal interface with oxidation was formed. The thermoelectromotive force due to the temperature gradient in the generator was measured for the open circuit condition, and the thermoelectromotive force of the generator with the oxidized interface was about 3 times greater than that of the generator without oxidation. The maximum powers of the generators with and without oxidation were determined from the current–voltage characteristics measured for the closed circuit condition, and it was verified that oxidizing the bi-metal interface was effective in enhancing the performance of the thermoelectric power generator. For example, the maximum power of the generator with the oxidized bi-metal interface was about 0.3 μW at a temperature difference as low as 40 K, and this value was greater than that of the generator without oxidation.

1. Introduction

The use of renewable energy generated from wind [1,2], solar [3–5], heat [6–23], vibration [24,25], etc. is a worldwide phenomenon. Among these 'clean energy' sources, heat is an energy source that can be easily accessed in our daily lives. Usually, the Seebeck effect is instrumental in generating power from heat, and the phenomenon can be explained simply by considering an electrical circuit comprising bi-metal wires. If there is a temperature gradient between two bi-metal junctions, a thermoelectromotive force, ΔV, appears in the circuit and this is given by.

$$\Delta \mathrm{V} = S(T_\mathrm{H} - T_\mathrm{L}), \tag{1}$$

where $S(=\alpha_1 - \alpha_2)$ is the Seebeck coefficient of the circuit, and α_1 and α_2 are the absolute thermoelectric powers of each metal wire. T_H and T_L are the temperatures of the hot and cold junctions. Regarding Eq. (1), combining wires that have large differences in their values of α_1 and α_2 can effectively enhance ΔV [18,19]. Also, inducing a large temperature gradient in the circuit is a key element for efficiently generating ΔV. Moreover, the use of nanostructures has been found to be effective in enhancing performance in thermoelectric applications [12,14,16,20].

Up till now, the use of thermoelectric power generators in our daily lives has been limited due to various reasons. For example, to expand the use of thermoelectric power generation, thermoelectric materials which can realize high efficiency and are not to be limited in natural resources are indispensable. Especially, the available temperature differences normally encountered in our life space are not very high. Therefore, there is a need for thermoelectric power generators that can generate power from small temperature differences, and various kinds of devices have been proposed and realized for this purpose [11, 20,22,23]. Yadav et al. fabricated flexible thermoelectric power generators having the Ni–Ag junctions and realized the maximum power of 2 nW for 7 couples at the temperature difference of 6.6 K [11]. Nonoguchi et al. fabricated a fully bendable thermoelectric module with the air-stable n-type single walled carbon nanotubes and realized the power of around 100 nW for 3couples at the temperature difference of 20 K [22]. Cao et al. fabricated the bismuth tellurium–antimony tellurium based flexible thermocouples using screen printing technology and realized the maximum power of 444 nW for the device size of around 60×20 mm^2 at the temperature difference of 20 K [23].

In this paper, a plate-type thermoelectric power generator (TPG) that was composed of an Fe plate and an Al layer was fabricated to realize power generation derived from a small temperature difference. The thermoelectromotive force induced by temperature gradients of up to 60 K was measured in the fabricated TPG for the open circuit condition. Moreover, the maximum power of the TPG in this temperature range was estimated from the current–voltage characteristic measured for the closed circuit condition. Both the thermoelectromotive force and the maximum power of the TPG with the oxidized bi-metal interface were greater than those of the TPG without oxidation, and it was verified that oxidizing the bi-metal interface was effective in enhancing the efficiency of power generation.

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2. Proposed thermoelectric power generator

Fig. 1(a) shows the concept and the structure of the plate-type TPG proposed in this paper. For the materials for the bi-metal interface we considered combining Fe, which, among the minor-metal-free materials has high absolute thermoelectric power [21], with Al, which has relatively low absolute thermoelectric power. The values of the absolute thermoelectric powers of Fe and Al are $+16.2$ μV K^{-1} and -1.66 μV K^{-1} [26], respectively. The Al layer was deposited on an Fe plate partially covered with an insulating layer; thus, an Fe/Al interface was realized on the exposed part of the Fe plate. If the temperature of the bi-metal interface side, T_H, is relatively higher than that of the insulation side, T_L, a voltage ΔV appears due to the temperature difference, $\Delta T (= T_H - T_L)$, such that the electrical potential on the Al side becomes positive for this materials combination. Previously, huge values of absolute thermoelectric power have been reported elsewhere for oxide materials [27]. We therefore oxidized the surface of the Fe plate before depositing the Al layer in order to enhance the thermoelectric power generation efficiency.

The surface of the Fe plate (100 μm thick) was oxidized in a furnace at 873 K for 3 h. The oxidized Fe plate was then covered with a resist mask, and a SiO_2 layer was formed on the Fe plate for electrical insulation. After removing the resist mask, an Al layer was deposited on the SiO_2 layer by radio frequency sputtering, completing the process. A bi-metal interface was realized between the oxidized Fe and the Al on the exposed part of the Fe plate. The thickness chosen for the SiO_2 layer was 3 μm. The Al layer was 5 μm thick. The dimensions of the TPG were 30 mm in length and 20 mm in width, and the length of the bi-metal interface, L_B, was 5 mm; see Fig. 1(b). Conductive wires were attached on both the Fe and Al surfaces using conductive tape.

Fig. 2(a) shows a scanning electron microscope (SEM) micrograph of the cross-section at the bi-metal interface of the fabricated TPG, and the

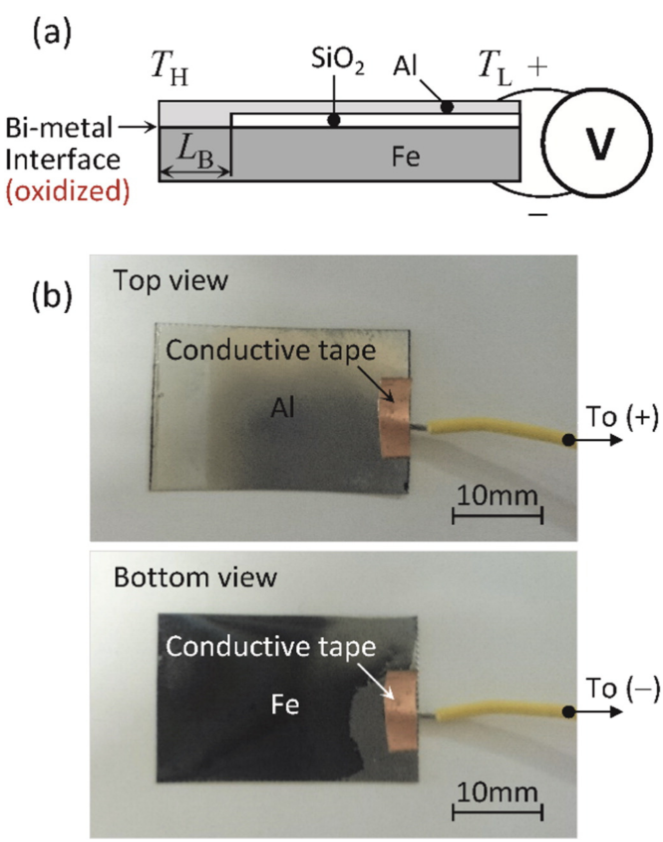

Fig. 1. Plate-type thermoelectric power generator (TPG). (a) Concept. The bi-metal interface was composed of oxidized Fe and Al. (b) Top and bottom views of the fabricated TPG.

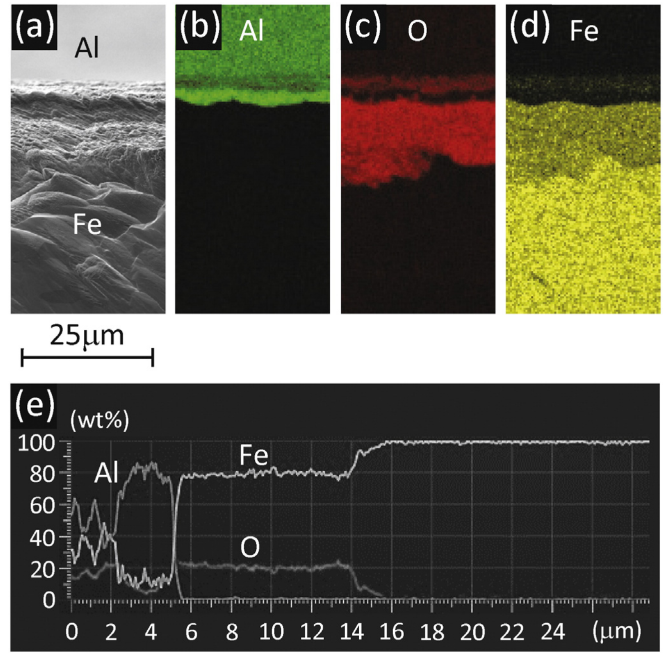

Fig. 2. (a) SEM photograph of the oxidized bi-metal interface. Elemental distributions in the corresponding area obtained by EDX for (b) Al, (c) O and (d) Fe, respectively. (e) Profiles of each element across the bi-metal interface. Results of EDX analysis clearly showed that the surface of the Fe was definitely oxidized and that the thickness of the oxide was about 10 μm.

elements Al, O, Fe detected at the corresponding area by energy dispersive X-ray spectroscopy (EDX) are shown in Figs. 2(b) to (d), respectively. Also the profile of each element across the bi-metal interface is displayed in Fig. 2(e). The results of EDX clearly showed that the surface of the Fe was definitely oxidized and that the thickness of oxide was around 10 μm. To confirm the effect of the oxidation at the bi-metal interface on the performance of the TPG, we prepared other TPGs with the same structure, materials and dimensions but without oxidizing the bi-metal interface. No discernible oxygen was detected by EDX analysis at the bi-metal interface of the TPG without oxidation.

3. Results and discussion

3.1. Open circuit condition

The conductive wires on both the Fe and Al surfaces were connected to a voltmeter, where the wires attached on the Al and the Fe were connected to the positive and the negative terminals, respectively. A heater with dimensions of 10×20 mm was attached on a part of the Al surface, and ΔV due to the temperature gradient in the TPG was measured. Here, the heater was rigidly clamped with a mechanical jig to realize good thermal contact between the heater and the surface of the TPG, and the temperature of the heater was precisely controlled by a temperature controller. The heating area was 10×5 mm. Fig. 3(a) shows an example of the temperature distribution on the surface of the TPG obtained from the Al side by an infrared camera. In the measurement, to realize the accurate temperature measurement, the surface of the Al was covered with a masking tape having the high emissivity. The temperature distribution shown in Fig. 3(a) was obtained 1 min later after the temperature of the heater reached set value, and at this moment, the temperature distribution reached steady state value. The temperature of the heater is denoted by T_H and that of the edge of the TPG by T_L, and $\Delta T (= T_H - T_L)$ was 40 K for this case. It is noted that the temperature distributions of the fabricated three TPGs induced by the heater were similar for each set values of the heater.