Flexible Sheet-type Thermoelectric Generators for Energy Harvesting

Tsuyoshi Muto*, Kunihisa Kato* and Wataru Morita*

*Lintec Corporation, Research Center, 336-0026, Japan, ts-mutou@post.lintec.co.jp

ABSTRACT

We describe prototype production of sheet-type thermoelectric power generation modules using the printable thermoelectric materials and flexible sheet substrate. By the use of the printed electronics processes, the degree of freedom in designing the size and shape of the modules were improved. The power generation scale of a module has about 60 cm^2 active area reached to sub m W order at a temperature region below 100 ^oC.

Keywords: thermoelectric generator, flexible, sheet-type, energy harvesting

1 INTRODUCTION

Seebeck type thermoelectric (TE) generators are one of the promising devices for the waste heat conversion to the electricity as well as the energy harvesters at a temperature range between room temperature and 200^oC. The heat-to-electricity conversion efficiency of the TE generators is reached to 10 % at the TE figure of merit (*ZT*) of 1 [1]. As a class of power generating devices, the TE generator lacks mechanical motion part unlike to the reciprocating electric generators. From this feature, the devices are suitable for miniaturization of the sizes, especially reduced thickness, and anticipated to the maintenance free behavior for the long time use.

In our former report, we introduced TE ink material suitable for printing production of the TE devices [2]. These materials are based on bismuth telluride (Bi_2Te_3) compounds and some additives, and the printed materials post thermal annealing showed *ZT* of 0.7 and 0.4 using the *p*- and *n*-type thermoelectric semiconductors, respectively. In this paper, we describe prototype production of the sheet-type TE generator using the ink materials and flexible substrate having patterned metal electrodes. Power generation ability of the TE modules were examined as a function of temperature difference applied to the sheet type modules. As expected from its plastic substrate, the modules show high flexibility, and the possibility of application of the TE modules for the wearable electronics and the internet of the things fields was also discussed.

2 EXPERIMENTAL

2.1 TE Materials Preparation

Granular TE materials (*p*- and *n*-type Bi-Te-X intermetallic compounds, D_{50} are about 200 μm) were ground to powdery form using the jet milling apparatus under an inert atmosphere. Each of fine powders was dispersed in the thermosetting binder formulation. A typical mixed ratio between TE powder (D_{50} < 1.0 μm) and the binder was 90/10 wt/wt. The obtained slurry was stored at ambient conditions and used for the module fabrication as the TE ink.

Small chips obtained by thermal curing of the inks having restricted cross-section area and length were used for electrical and thermoelectrical characterization. Electrical conductivity and Seebeck coefficient of the TE chips were corrected by a thermoelectric analyzer (ZEM-3, Advance-Riko). Thermal conductivity was measured by the 3ω method [3].

2.2 Fabrication of TE Modules

Plastic (polyimide, PI) film substrate laminated with thin metal foil (Cu or Ni) are used as a flexible substrate. The metal layer was patterned by using the photolithography processes and used as the patterned electrodes. After some surface modification, the metal electrodes on the films were partly covered with the *p*- or *n*-type TE ink. Patterning of the ink was achieved by a common screen printing. Firstly, either the *p*- or *n*-type ink was patterned on the electrode and dried by baking in air. Afterward, the opposite carrier type ink was patterned on the same substrate at alternative positions that filling vacant space of the electrode surface. Result of the *p*- and *n*-type ink printing, the substrate makes a TE generator circuit having designed parallel/serial electrical divergence. The printed TE layers were completely immobilized by sintering below 400 ^oC. The head and tail sides of the substrates were laminated with heat conducting metal bars with double-sided adhesive sheets and used for further characterization. A module appearance is shown in Fig.1(a).

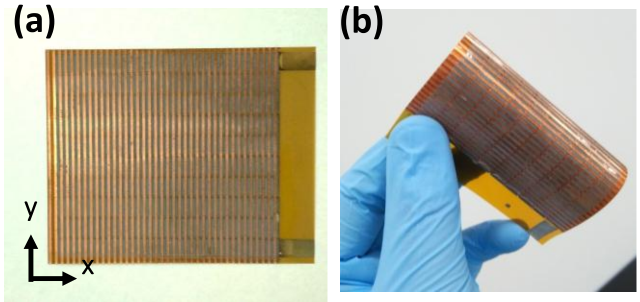

Fig.1 TE module prepared in present work: (a) typical module appearance; (b) module bended along the x-axis.

2.3 Characterization of Module Performance

The power generation of the sheet-type module was examined by measuring the internal electrical resistance, R, [Ω], and output voltage under controlled temperature difference, ΔT, [°C], by using a digital multimeter. The ΔT control was performed by a combination of a water cooling heat sink and a hot plate. Local temperature of each positions were directly measured by the K-type thermocouple equipped with a multichannel data logger.

Maximum output power ($P_{\max}$, [W]) of a TE module is expressed by the following equation (1) [4]:

$$P_{\max} = V_0^2/4R \quad (1)$$

where V is total voltage generated from TE legs [V], and R is the internal resistance of a module.

As shown in Fig.1(b), our module is flexible particularly for the x-axis direction in Fig.1(a). On the other hand, reversible bending for the y-axis direction was prohibited by the presence of the rigid metal bars on both sides of the module. Thus, we took internal resistance, R, data under the x-axis direction bending at bending radius of 10~40 mm using the cylindrical plastic rods.

3 RESULTS AND DISCUSSION

3.1 Electrical and Thermoelectrical Properties of TE Materials

Typical property of the ink material is summarized in Table 1 with the conventional bulk material data for a comparison. Owing to the presence of the thermosetting binder, the ink showed about one-fifth of the κ of bulk material, and smaller κ is a positive effect to its rather large ZT in equation (2) under constant temperature.

Table 1: Comparison of electrical and thermoelectrical properties of the p-type TE ink and common bulk material

Sample	σ [S cm^{-1}]	S [μV K^{-1}]	κ [W (m^{-1}K^{-1})]	ZT
TE ink	150	220	0.31	0.7
$Bi_{0.4}Sb_{1.6}Te_{3.0}$ [5]	850	205	1.4	1.0

On the other hand, the decreasing of σ is considered as a negative effect for the TE performance of the ink material.

$$ZT\,[-] = \sigma S^2 \kappa^{-1}\, T \quad (2)$$

where σ is electrical conductivity, S is Seebeck coefficient, and κ is thermal conductivity.

Because of the presence of low κ binder material in the TE ink, the electronic and thermal conduction paths in the TE materials were shortened and showed smaller σ and κ. However our thermosetting binder showed antistatic level electrical conductivity (R_s >1 x 10^9 ohm sq^{-1}), the investigation of the rather large σ, 150 S cm^{-1}, of the TE material is under way.

The plastic substrates, such as heat resisting PI films, are applicable to the TE module platform.

3.2 TE Module Performance and Potential Application as Energy Harvester

The use of the plastic substrates and an appropriate thermal design, the flexible TE modules have a total thickness of 0.4 mm were obtained. Fig.2 exhibits ΔT dependence of output power and open circuit voltage (V_{oc}, [V]) of a TE module has an active area of 75 x 75 mm^2. As observed from the plot, the output power was reaching to 0.1 and 0.5 mW at ΔT of 15 and 30 °C, respectively.

Considering the life space of the human, these ΔT correspond to the difference between human skin temperature (*ca*. 34 °C) [6] and mean air temperature 13.3 °C (at Washington D.C., U.S.) [7] for example (ΔT = 20.7 °C). This ΔT generates about 0.2 mW output power and sufficient for the potential use for low power wireless technologies [8]. In the practical cases, driving of the low power wireless modules by the TE sheet modules require the DC-DC converting technique such as the current and voltage boosters. Despite of the low possibility of the sequential signal dispatch, the TE module will applicable to the stand-alone DC power source particularly for the "wearable electronics" field [9].

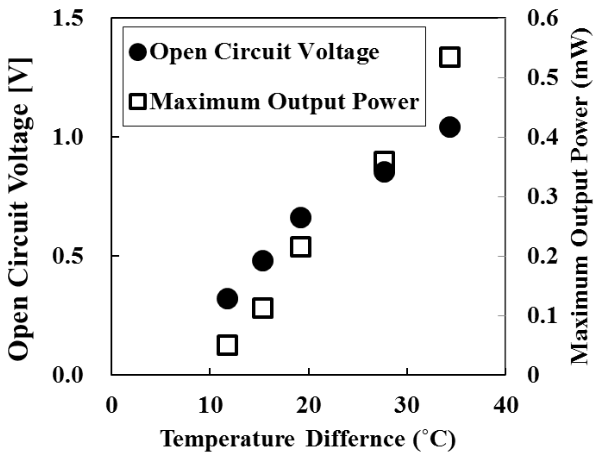

Fig.2 ΔT dependence of output power and V_{oc} of a TE module has an active area of 75 x 75 mm^2. The ΔT indicates temperature difference between *'head'* and *'tail'* sides of the module.

From the wearable electronics point of view, the flexible or bendable feature of the modules increases its value. The flexible modules are bendable at the in- and outfold bending diameter of 20 mm, and the internal resistance was

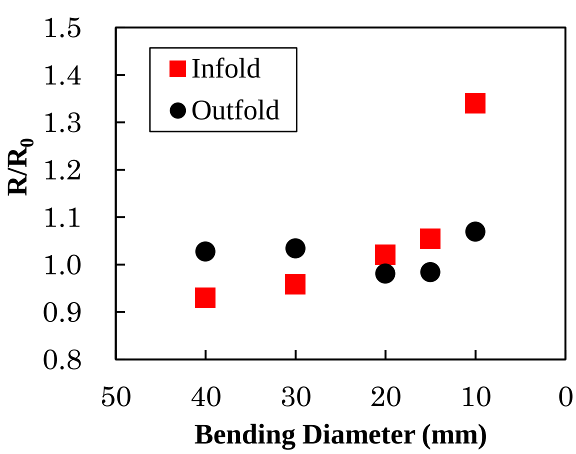

Fig.3 Relation between bending diameter and R/R_0 of TE module with a size of 75x75x0.4 mm^3. R_0 and R is an internal resistance at initial (bending angle of 0°) and bended states, respectively, for the module. Each of R values are taken at bending angle of 180°, and the bending direction is maintained at the x-axis direction depicted in Fig.1(a).

unchanged during the released and bended states over bending diameter of 20 mm (Fig.3).

From these features, the sheet-like TE generators described here are possible candidates for the energy harvesters installable to the heat source surface have a versatile sizes (1 x 10^{-3}~10^0 m), shapes, and dimensions.

4 CONCLUSION

Formation of the TE layer was achieved by the conventional printed electronics (PE) processes. By the use of the PE processes, the degree of freedom in designing the size and shape of our TE modules are improved. Actually, we obtained the short (few millimeters in the longest axis) and long (few 10 centimeters in length) modules with relevant substrates.

Owing to its bendable or flexible feature, our TE modules are potentially applicable to the stand-alone power source for the low power wireless system through the wearable applications. Possible curvature of the modules will covers human limbs and body surfaces. Considering to the inanimate object application, the very small thickness expands its usage. Automated monitoring and data mining systems through the Machine-to-Machine (M2M) or Internet of the Thing (IoT) are also our target applications in the near future.

REFERENCES

[1] M. Xie and D. M. Gruen, "Potential Impact of ZT = 4 Thermoelectric Materials on Solar Thermal Energy Conversion Technologies", *J. Phys. Chem. B*, 114, 14339-14342, 2010.

[2] K. Kato, T. Muto, T. Kondo, and K. Miyazaki, "Screen-printed sheet type thermoelectric module for power generation", *MRS Fall meeting* (oral presentation, Boston), 2015.

[3] M. Takashiri, M. Takiishi, S. Tanaka, K. Miyazaki, and H. Tsukamoto, "Thermoelectric properties of n-type nanocrystalline bismuth-telluride-based thin films deposited by flash evaporation". *Journal of Applied physics*, 101(7), 074301, 2007.

[4] I. S. Ike, I. Sigalas, S. Iyuke, and K. I. Ozoemena, "An overview of mathematical modeling of electrochemical supercapacitors/ultracapacitors", *J. Power Sources*, *273*(1), 264-277, 2015.

[5] L. P. Bulat, I. A. Drabkin, V. V. Karatayev, V. B. Osvenskii, Y. N. Parkhomenko, M. G. Lavrentev, A. I. Sorokin, D. A. Pshenai-Severin, V. D. Blank, G. I. Pivovarov, V. T. Bublik, and N. Y. Tabachkova,

"Structure and Transport Properties of Bulk Nano thermoelectrics Based on $Bi_xSb_{2-x}Te_3$ Fabricated by SPS Method", *Journal of Electronic Materials*, 42(7), 2110-2113, 2013.
[6] D. I. Sessler, "Temperature monitoring and perioperative thermoregulation." *J. Am. Soc. Anesthesiologists*, 109(2), 318-338, 2008.
[7] P. D. Jones, M. New, D. E. Parker, S. Martin, and I. G. Rigor, "Surface air temperature and its changes over the past 150 years", *Reviews of Geophysics*, 37(2), 173-199, 1999.
[8] C. Gomez, J. Oller, and J. Paradells, "Overview and Evaluation of Bluetooth Low Energy, An Emerging Low-Power Wireless Technology", *Sensors*, 12(9), 11734-11753, 2012.
[9] P. Lam and S. Tang, "Recent developments in flexible wearable electronics for monitoring applications", *Transactions of the Institute of Measurement and Control*, 29(3-4), 283-300, 2007.

* Lintec Corporation, Research center, 7-7-3 Tsuji, Minami-ku, Saitama-shi, Saitama 336-0026 Japan,
Ph +81-48-711-9893, Fax +81-48-711-9895,
ts-mutou@post.lintec.co.jp