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Design of linear shaped thermoelectric generator and self-integration using shape memory alloy

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A segmented linear-shaped thermoelectric generator was designed with n-type Mg_2Si and p-type higher manganese silicide as higher temperature segments and n-type and p-type Bi–Te based compounds as low temperature legs. A new design of a dovetail-shaped AlN–Cu composite as an electrode enabled linear-shaped thermoelectric generator to be securely bonded to the combustion chamber walls by using shrink-fit-joining method. As-assembled linear thermoelectric generator is lighter in generating more power output as compared with conventional π-shaped thermoelectric generator. The linear thermoelectric module generates the output power of 0.513 W under 500 °C temperature difference and the specific power density was measured at 89.3 W/kg, the output power was improved by 7% and the specific power density more than 2 times, as compared with those of the π-shaped thermoelectric module based on the same set of thermoelectric materials and temperature differential.

1. Introduction

Thermoelectric (TE) devices have been used in a wide range of applications for energy harvesting systems by converting thermal energy directly to electrical energy [1–4]. The performance of TE materials is determined by the dimensionless figure of merit (ZT) which is defined as,

$$ZT = \frac{S^2\sigma}{\kappa}T \quad (1)$$

where S, σ, κ and T are the Seebeck coefficient, electrical conductivity, thermal conductivity and the absolute temperature at which the properties are measured, respectively. Recently, energy harvesting devices using TE generator (TEG) modules have been applied to air-borne applications [5,6] to increase fuel efficiency by recapturing wasted exhaust heat and converting it to useable electricity [7].

The conventional TEG is single-stage couples connecting electrically in series and thermally in parallel with π-shape design. A typical π-shaped TEG is made by connecting N pairs of n-type and p-type TE legs, which gives rise to the output voltage proportional to N. To design higher power output, Harman [8] suggested the cascaded design of stacking two or more π-shaped TEGs. TE module at lower legs consisting of TE materials working best for low temperature range generates power from the heat rejected by the upper module based on TE legs operating at high temperature. This design has a disadvantage for weight sensitive applications because extra ceramic substrates and metal electrodes increase the total weight of the device. One way to improve the TE performance as well as to minimize the total weight of the device is the segmented design by dividing the n-type and p-type legs into several segments using different TE materials [9,10]. However, the π-shaped planar structure becomes unstable if the length of n-type and p-type TE column is not identical, which makes the TEG module weak at high temperature environment. Stockholm [11] introduced a linear design concept of TE module where an electric current flows in a straight line through the TE legs while the electric current in the π-shaped TEG design flows alternatively up and down. Crane and Bell [12] showed the aspect ratio of n-type in the linear TEG design can be controlled with that of p-type independently. Sakamoto et al. [13] designed a linear-shaped TEG for high temperature range by using only n-type TE element, which has a limit of scaling up by connecting a number of n-type uni-legs electrically in series and thermally in parallel. However, the reported TEGs used bulk Cu or stainless steel as electrodes, which are the main source of increasing the total device's weight. In addition, ceramic substrates on top and bottom sides of the module are still required to avoid short-circuiting.

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In this study, an advanced design of the segmented linear TEG is proposed for its integration into the walls of a combustion engine system in unmanned aerial vehicles (UAV) with two innovative designs: (a) dovetail-shaped electrode based on a composite of copper (Cu) and aluminum nitride (AlN), and (b) self-jointing by shrink-fit behavior of Fe-based shape memory alloy (Fe-SMA). As the high temperature TE segments, bulk Mg_2Si of n-type and higher manganese silicide (HMS, $MnSi_{2-x}$, x = 0.250–0.273) of p-type are used since they are light-weight, non-toxic and low-cost TE compounds working for high temperature range. In the following, we will discuss linear-shaped TEG design and also its performance as compared with π-shaped TE module.

2. Preparation of TE segments

For accurate comparison with the π-shaped segmented TEG reported by Kim [14], the same set of TE segments are used to assemble linear-shaped TEG in this study. All TE legs in linear-shaped TEG were synthesized and prepared from the same TE materials used in the π-shaped TEG so that the measured TE properties of each segment in our previous study can be utilized to predict the performance of π-shaped and linear-shaped TEGs. The following states briefly the preparation of TE segments.

Bi doped Mg_2Si was fabricated as n-type segment on the high temperature side. Mg (99.95%), Si (99.9999%) and Bi (99.999%) were prepared with Mg:Si ratio of 67:33 (at%) including the Bi dopant (3 at%) and polycrystalline Mg_2Si was synthesized by an electric furnace [15]. The obtained ingot was ground into powder using planetary ball milling technique, and the powder was transferred to a glove box with Ar atmosphere to set up in a graphite die for spark plasma sintering (SPS) (Sumitomo Coal Mining Co., Ltd., Dr. Sinter 1020S). The assembled set of graphite die and punches was heated in a two-step procedure of SPS, where the first pre-heating step allows one to maintain low vacuum level by holding the temperature at 500 °C with the pressure of 30 MPa. For the second step, the graphite set was pressurized up to 50 MPa while it was heated to 750 °C and kept for 3 min with a heating rate of 100 °C/min [14]. The sintered Mg_2Si pellet of 15 mm diameter was cut into rectangular pillars of 4 mm × 4 mm × 5 mm by a diamond saw.

To fabricate p-type HMS segment which is for the high temperature leg, Mn (99.9%) and Si (99.9%) were individually put into an alumina jar with alumina balls, and mechanical grinding was carried out in vibration ball milling equipment for 10 h in Ar atmosphere, where the ball to powder volume ratio was 20:1 [16]. The ground powders were blended with Mn:Si ratio of 35.5:64.5 (at%) in a rotary mixer at 100 rpm for 1 h in Ar atmosphere, then the mixed powders were transferred into the graphite mold of 20 mm diameter [16]. The HMS disk was sintered by SPS process at 900 °C and 30 MPa for 15 min in a vacuum. As-sintered HMS was diced into 4 mm × 4 mm × 3.4 mm by a diamond saw.

As TE segments for low temperature legs, both n-type and p-type Bi-Te based compounds were purchased from Tellurex Inc. in the shape of 4 mm × 4 mm × 1 mm and 4 mm × 4 mm × 2.6 mm, respectively.

TE properties of all TE segments were evaluated. The Seebeck coefficient (S) and electrical conductivity (σ) were measured as a function of temperature using Ulvac-Rico, ZEM-3 with the bar sample in size of 2 mm × 2 mm × 10 mm. The thermal conductivity (κ) a disk sample of 1 mm thickness and 10 mm diameter was measured as a function of temperature by using a laser flash system (Ulvac-Rico, TC-9000). The measurements of TE properties of Bi-Te alloys were carried out over the temperature range from room temperature to 300 °C while those of Mg–Si and HMS from room temperature up to 600 °C. Fig. 1 shows the temperature dependent TE properties, where p-type Bi–Te, n-type Mg–Si and p-type HMS were the average values based on the five independent measurements shown as error bars in Fig. 1(a–d) by the above measurement

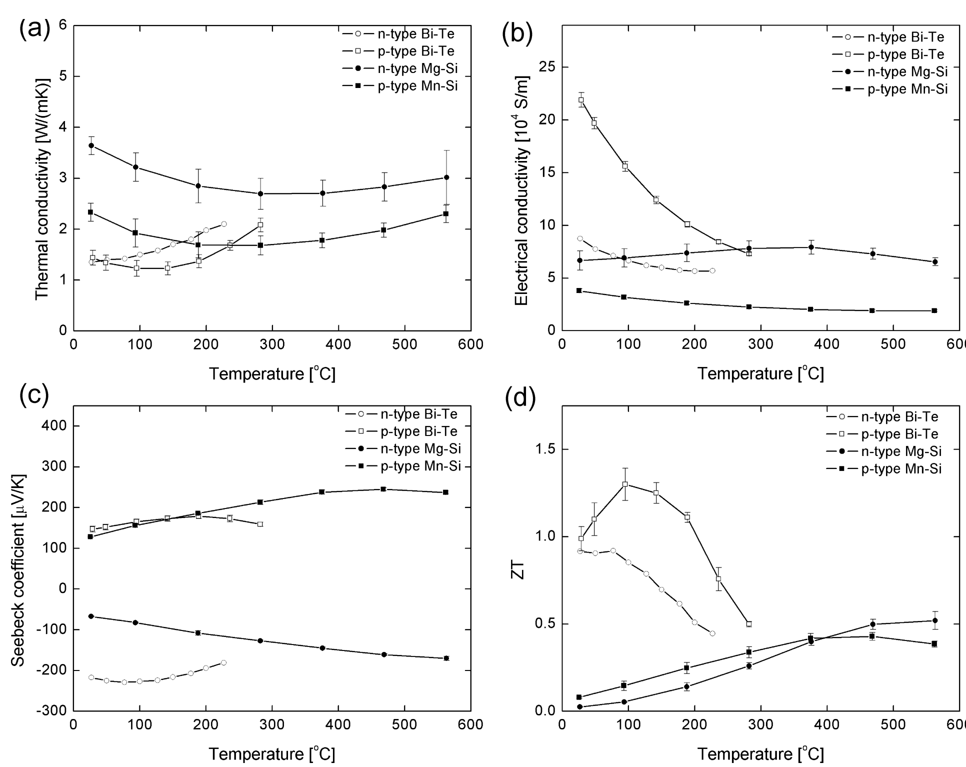

Fig. 1. Temperature dependent TE properties of n-type Mg_2Si and p-type HMS as high temperature segment, and n-type Bi–Te–Se and p-type Bi–Sb–Te as low temperature segment, in which the same set of TE segments are utilized in the work of Kim [14]: (a) thermal conductivity, (b) electrical conductivity, (c) Seebeck coefficient, and (d) dimensionless the figure of merit, ZT.