MEASUREMENT OF THE FIGURE-OF-MERIT OF THERMOELECTRIC DEVICES

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Abstract: The apparatus for evaluation of the figure of merit (*ZT*) of thermoelectric devices has been developed. *ZT* value is comprised of three physical quantities, Seebeck coefficient, electrical conductivity, and thermal conductivity. However, to date, the *ZT* values of the thermoelectric devices have been evaluated by Harman method due to difficulty in measuring thermal conductivity of the devices with high accuracy. In this study, we present new apparatus developed for evaluating the thermoelectric figure of merit of devices by direct measurement of thermal conductivity using guarded hot plate method.

Keywords: thermoelectric, figure of merit, seebeck coefficient, thermal conductivity, guarded hot plate method.

1. INTRODUCTION

Thermoelectric effects become more and more a field of interest for the industry, because heat and cold can be generated by thermoelectric materials directly from an electrical current. On the other hand electric current can be produced directly from a heat flow due to temperature difference between two sides of the thermoelectric device. With the growing public interest in environmental problems in recent years, the importance of thermoelectric power generation is being re-recognized and an invention of the thermoelectric devices with high efficiency is quite important along with the development of thermoelectric materials. Thermoelectric heat-to-electrical power converters also have potential uses in thermal energy recovery systems.

The thermoelectric power generation efficiency depends on the thermoelectric figure of merit, *Z*, of the thermoelectric materials of which the thermoelectric device is comprised. This quantity is a combination of the thermoelectric power or Seebeck coefficient S, the electrical of the material [1]:

$$Z = \frac{S^2 \sigma}{\kappa} \qquad (1)$$

Technique for evaluating *Z* in precise is most important for developing high efficient thermoelectric materials and devices. One must be careful in the evaluation of *Z*. The electrical conductivity and Seebeck coefficient can be determined with high accuracy and showed consistency between the measured values by different researchers. However, some inconsistencies arise in the *Z* value obtained in different laboratories, which are mainly due to differences in the observed thermal conductivity of the thermoelectric materials and devices.

The quantitative evaluation of the figure of merit of thermoelectric materials and devices has been made by the Harman method [2]. In this method, a dimensionless figure of merit ZT is given by equation:

$$ZT = \frac{V_{dc}}{V_{ac}} - 1 \qquad (2)$$

Where, V_{ac} and V_{dc} is a direct and an alternating current applied to the sample, respectively. Eq. (2) is equivalent to Eq. (1) when the thermally isolated condition of the sample is guaranteed. However, the heat leakage by the current and voltage lead wires and the degree of vacuum around a sample cannot be precisely estimated. Even though difficulty in making a perfect adiabatic condition these condition, the Harman method has been considered as a very simple technique and can provide a value of *ZT*. However, it should be noted that the Harman method was introduced to overcome the difficulty in precise and simultaneous measurement of all physical quantit .
Especially, most difficult problem arises in precise measurement of thermal conductivity of the device.

In this study, we present new apparatus for evaluation of figure of merit of thermoelectric devices by direct measurement of the three physical parameters, Seebeck coefficient S, the electrical conductivity , and the thermal conductivity. Especially, this method described here will give a way to measure the exact value of thermal conductivity of the device. For this, we introduced guarded hot plate principle to our apparatus, which has been considered as most accurate method for thermal conductivity measurement. This method is available in the wide temperature range from liquid nitrogen point to high temperatures.

2. APPARATUS

The schematic diagram of the developed system for evaluation of figure of merit of thermoelectric devices is shown in Fig. 1. This apparatus is composed of three parts, a measuring assembly unit, a control part, and a data acquisition and processing part. The main part of the

apparatus is a measuring assembly unit and its temperature is controlled by PID control. For precise measurement, the measuring assembly part is installed in vacuum chamber. System control, communication between measurement units and computer, and data processing was run using the LabView software package.
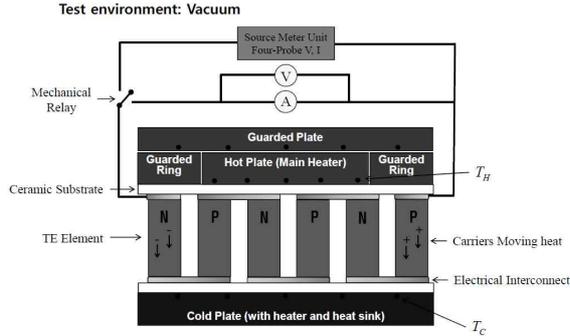

Figure 1 Schematic diagram of measuring assembly unit.

2.1 The main part

The main part of the apparatus is composed of four temperature controlled plates (hot plate, cold plate, guarded ring, and guarded plate) as can be seen in Fig. 1. The temperatures of the plates are measured by 19 thermocouple thermometers embedded in the plates.

Temperature of the hot plate was monitored by 5 thermocouple temperature sensors embedded in the plate and was controlled using DC power supply and a proportional-integral-differential (PID) control. The temperature stability of the hot plate with time was determined as 0.01 ℃. Temperatures of three other plates, cold plate, guarded ring, and guarded plate, are controlled by three PID temperature controllers (RKC) independently and the temperature stability was about 0.02 ℃.

The electrical energy, Q (in the unit of watt), applying to the hot plate for maintaining steady state condition between hot and cold plate is determined by measuring the voltage and current of the hot plate.

The cold plate functions as heat sink by an external circulating chiller and the temperature of the cold plate is controlled by heating wire embedded in it. A temperature difference, ΔT, is established across the device by temperature control of the hot and cold plate ($\Delta T = T_H - T_C$, where, T_H and T_C are the temperature of the hot plate and that of the cold plate, respectively. When using ethanol as coolant of a circulating chiller, the temperature difference between hot plate and cold plate can be made up to 36 K. The measurement temperature is defined as this way;

$$T = \frac{T_H + T_C}{2} \qquad (3)$$

2.2 Thermal conductivity measurement

The guarded hot plate method is used to measure the thermal conductivity of the devices. The principle of the guarded hot plate method is to generate a known unidirectional heat flux through the devices so that they appear as slabs of infinite width bounded by parallel planes.

To achieve this aim, it is customary to use a heater plate comprising two parts, a hot plate (or metering area) surrounded by a guard ring and separated from it by a small air gap, which acts as a thermal barrier. Also another guarded plate is placed on top of the heater plate with a small air gap as shown in Fig. 1. Heat flows from the metering area of the heater plate through the specimens only to cold plates maintained at stable lower temperature constant to within a few hundredths of a degree Celsius due to the guarded heaters (guarded ring and guarded plate). Electrical current is supplied to the guards independently of the metering area heater and the heat flux produced serves to maintain the heat flow perpendicular to the hot face in the central metering region, thereby creating isothermal planes across the measured region of the specimen. Under these conditions, the thermal conductivity, κ, was deduced from the power supplied, Q, the mean difference in temperature between the cold and hot plate, $\Delta T = T_H - T_C$, the cross-sectional area of the plates, A, and the mean thickness of the devices, d, using an equation originally developed by Fourier for conduction of heat in one dimension [3];

$$\kappa = \frac{Qd}{A\Delta T} \qquad (4)$$

Our apparatus requires a single rectangular-shaped specimen with the dimension of 40 mm × 40 mm ~ 100 mm × 100 mm because of the size of the metering area of the heater, 30 mm × 30 mm. The unidirectional heat flux condition is most important for an accurate measurement of the thermal conductivity of the devices.

2.3 Seebeck coefficient measurement

When the desired temperature difference across the thermoelectric device, the thermoelectric potential difference, $\Delta V / \Delta T$, is measured using voltage leads attached to the end of the device without any induced current. Seebeck coefficients are made in steady state by sweeping the temperature gradient, ΔT, and measuring the corresponding thermal voltage, ΔV. The Seebeck coefficient can be expressed using this equation [4];

$$S = \frac{\Delta V}{\Delta T} \qquad (5)$$

In this manner, the slope of the line, $\Delta V / \Delta T$, can be used to determine the Seebeck coefficient. Seebeck coefficient S includes both the device and the lead contribution. The linear relationship between ΔV and ΔT could be obtained and the Seebeck coefficient can be easily determined.

2.4 Electrical conductivity measurement

Electrical current and voltage can be measured with very high precision. Accurate evaluation of electrical resistivity (or electrical conductivity) requires that contact resistances to the sample and thermoelectric effects due to sample heating are minimized. Electrical conductivity measurements are usually the most accurate of all thermoelectric measurements and can be expressed like this equation.

$$\sigma = \frac{JL}{Va} \qquad (6)$$

where a, V, J, and L are the sample cross-section, the potential drop between two points of potential probe, the total current through the A, and total length between two points of potential probe, respectively. In our system, the four-probe method is used to measure electrical resistivity, which virtually eliminates the influence of contact resistance. The spurious voltage originating from thermoelectric effects can be eliminated by alternate current (AC measurements) and by very fast measurement using direct current (DC measurements). We used the DC measurements for electrical conductivity, in which method the measurement should be done at very short delay time less than 1 millisecond. We measured voltage and current applied to the thermoelectric device within 0.1 millisecond using four point method (Keithley 2636A SourceMeter).

2.5 Device under test

We purchased a single stage thermoelectric device from Melcor (USA). The number of p-n pair of thermoelectric material comprising the device is 119. We measured ZT value and power generation efficiency of the thermoelectric device at room temperature, 293 K. The temperature difference, ΔT, was changed from 0 K to 20 K with the step of 2 K.

3. RESULTS AND DISCUSSIONS

3.1 *ZT* value determination

Here, we would like to define *ZT* value as one per p-n pair of the thermoelectric materials comprising the thermoelectric device because the measured electrical conductivity and thermal conductivity is same to the values normalized by the number of p-n pairs of the thermoelectric materials. Also the value obtained using Eq. (2) also does not represent overall property of the devices. The first term on the right side of Eq. (2) is not the overall value of the device, but the ratio of voltage drop across the input and output point of the device when applying DC to that when applying AC. The result of the *ZT* value obtained using our developed apparatus is about 0.7 at 293 K. This value shows slightly small value compared to the literature values of TE materials (for examples, Bi2Te3). It has been known that the *ZT* value of the device is lower than that of low materials because of packing, soldering, and electrical connector materials in the device.

3.2 Power generation efficiency

The power generation efficiency can be calculated using the measured ZT value and Eq. (7) [5].

$$\eta = \frac{\Delta T}{T_H} \frac{\sqrt{1+ZT}-1}{\sqrt{1+ZT}+T_C/T_H} \qquad (7)$$

The results for the power generation efficiency of the device are shown in the Fig. 2. The efficiency of the device varies with an increase of temperature difference.
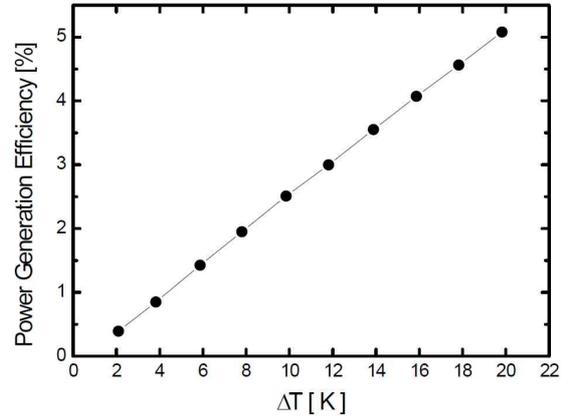

Figure 2 ZT values per p-n pairs of the thermoelectric materials measured at several temperature differences at 293 K

4. CONCLUSIONS

We developed new apparatus for evaluation of the figure of merit of thermoelectric device. The guarded hot plate principle was used to measure thermal conductivity of the device precisely. On top of that, the developed apparatus can be used to measure the electrical conductivity and the Seebeck coefficient of the thermoelectric device. This apparatus is first one that can evaluate *ZT* and simultaneously from direct measurement of three parameters, thermal conductivity, electrical conductivity, and Seebeck coefficient.

5. REFERENCES

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