Temperature difference dependence of coercivity of spin Seebeck voltage for BiY₂Fe₅O₁₂/Pt device made by metal organic decomposition method

Y. Takahashi, T. Takase, and K. Yamaguchi

Faculty of Symbiotic Systems Science, Fukushima Univ., 1 Kanayagawa, Fukushima-city, Fukushima 960-1296, Japan

The temperature difference ΔT and the thickness dependences of the spin Seebeck voltage (V_{SSE}) were investigated for the polycrystalline BiY₂Fe₅O₁₂/Pt device made by metal organic decomposition method. As a result of investigation of the ΔT dependence of V_{SSE} , it was shown that the coercivity of V_{SSE} largely changed at the certain temperature difference ΔT_g , and ΔT_g was decreased with the thickness of BiY₂Fe₅O₁₂ thin film increases. When $\Delta T > \Delta T_g$, the coercivity of V_{SSE} was almost the same as the coercivity of magnetization curve for the BiY₂Fe₅O₁₂/Pt device. On the other hand, when $\Delta T < \Delta T_g$, the coercivity of V_{SSE} was about twice as the coercivity of V_{SSE} when $\Delta T > \Delta T_g$. Focus attention on the remanence of V_{SSE} which the gap occurs in the coercivity of V_{SSE} is almost constant independently of the thickness of BiY₂Fe₅O₁₂ thin films.

Key words: spin Seebeck voltage, Bi:YIG/Pt device, metal organic decomposition method, temperature difference dependence, coercivity of V_{SSE}

1. Introduction

The "spin Seebeck device" is composed of two layers which ferromagnetic material and paramagnetic metal, and utilizes spin current generated by temperature gradient at the interface of two layers¹⁾. The device has characteristics, where the thermoelectric output (electric power) is increased simply by expanding the area of the device²⁾, different from the traditional "Seebeck device".

We have made the polycrystalline BiY₂Fe₅O₁₂ (Bi:YIG) thin film on an inexpensive quartz glass substrate by the metal organic decomposition (MOD) method³⁾ which can be easily applied to expanding the area. For the purpose of improving the electromotive force converted from spin Seebeck effect (hereafter, spin Seebeck voltage: V_{SSE}), we had investigated the best annealing temperature⁴⁾.

In this paper, we studied the temperature difference and the thickness dependences of V_{SSE} for the Bi:YIG/Pt device made based on the above method.

2. Experimental method

2.1 Making Bi:YIG/Pt device samples

Figure 1 shows the process for making Bi:YIG/Pt device samples. The substrate was used quartz glass with a length=13 mm, a width=7 mm, and a thickness= 0.45 mm. The Bi:YIG thin film was made by four steps as following: "(I) Spin Coat" of MOD solution on the substrate, "(II) Dry" to remove organic solvent, "(III) Pre-anneal" to decompose organometallic compounds and make them precursors of metal oxides, "(IV) Anneal" for crystallization. Here, the steps of "Spin Coat", "Dry", and "Pre-anneal" were repeated N times ($N = 3, 5, 10, 15, 20$) to change the thickness of the Bi:YIG thin film. Next, Pt thin film was formed by sputtering over the surface area of Bi:YIG thin film. In order to estimate the thickness of Bi:YIG thin film and Pt thin film, the cross

Fig. 1 Process for making Bi:YIG/Pt device samples.

Fig. 2 Experimental configuration of measuring V_{SSE} , T_{top} and T_{bot} for Bi:YIG/Pt device samples.

Corresponding author: Yuta Takahashi
(e-mail: fa0.mtyu715.0210@gmail.com)

Fig. 3 The time dependences of (a) T_{top} and (b) T_{bot} at each V_h in the sample ($N=20$) (c) The average of T_{top} and T_{bot} as a function of the V_h , and fitting line of $\bar{T}_{top}$ and $\bar{T}_{bot}$.

section for the sample ($N=10$) was observed by SEM. As a result, it was observed that the Bi:YIG thin film when $N=10$ was about 400 nm and the Pt thin film was about 10 nm. Finally, glass/Bi:YIG/Pt was annealed at 600 °C for 1 hour in an air atmosphere. For details on the process for making Bi:YIG/Pt device samples, refer to Ref 4).

Fig. 4 (a) M - H curves for each sample ($N=3, 5, 10, 15$, and 20) by VSM. (b) The coercivity H_c of M - H curves as a function of the N .

Fig. 5 (a) T dependences of M - H curves for the sample ($N=10$) by SQUID magnetometer. (b) The coercivity H_c of M - H curves as a function of the T .

2.2 Measurements of the magnetization and the V_{SSE} for Bi:YIG/Pt device samples

The Applied magnetic field H dependences of the magnetization M (M - H curves) for Bi:YIG/Pt device samples were measured by using vibrating sample magnetometer (VSM, Tamagawa Seisakujo; type TM-VSM1015) at room temperature. The absolute temperature dependences of M - H curves for Bi:YIG/Pt device samples were measured by using superconducting quantum interference device magnetometer (SQUID magnetometer, Quantum Design; MPMS). In both measurements, H was in the in-plane direction of the sample.

Figure 2 shows experimental configuration of measuring V_{SSE} for Bi:YIG/Pt device samples. When H was in the in-plane direction of the sample and the temperature gradient ∇T generated in the perpendicular direction of the sample, and electric potential difference between the electrodes of the sample perpendicular to each was measured as the V_{SSE} . The H was swept from -200 Oe to

200 Oe.

2.3 Measurement of the temperature of top and bottom of surfaces for Bi:YIG/Pt device samples

The temperature gradient was generated by the small ceramic heater (MISUMI; MMCPH) placed under the sample (bottom side). Temperature difference between top and bottom of surfaces ΔT was controlled by voltage of the power supply V_h applied to the heater. The stabilization of the temperature of top and bottom of surfaces of the sample, T_{top} and T_{bot} were confirmed, before measuring the ΔT dependence of the V_{SSE} shown in Sec. 2.2. Figure 2 shows the experimental configuration of measuring the T_{top} and T_{bot} for Bi:YIG/Pt device samples. The T_{top} and T_{bot} were each measured by two K-type thermocouples, after running the heater. The time dependences of T_{top} and T_{bot} at each V_h for the sample ($N=20$) are shown in Fig. 3(a) and (b), respectively. These can be shown, that was stable after 3000 sec, therefore, the average values from 4000 sec to 6000 sec as a function of the V_h are shown in Fig. 3(c), as $\overline{T_{top}}$, and $\overline{T_{bot}}$. Two solid lines are an approximate straight line to which the least squares method was used. The difference between these approximate straight lines is used as a conversion equation for V_h and the ΔT , as

below

$$\Delta T(K) = 0.73V_h - 2.0 \quad (1).$$

The same measurement was performed for each sample ($N=3, 5, 10$, and 15), and it was checked that Eq. (1) can be applied to these samples too. In this paper, the V_h is in the range of 5.0V to 15.0V (ΔT is from 1.7K to 9.0K, applying Eq. (1)), and the V_{SSE} was measured with increasing ΔT .

3. Experimental results

3.1 The thickness and the absolute temperature dependences of $M-H$ curves

The magnetic characteristics of the Bi:YIG/Pt device samples were investigated, before measuring the V_{SSE} .

Figure 4(a) shows the $M-H$ curves for each sample ($N=3, 5, 10, 15$, and 20) by using VSM. It was illustrated that the M increased with increasing the N , each M was 1.9×10^{-4} , 4.5×10^{-4} , 9.3×10^{-4} , 2.0×10^{-3} , and 2.6×10^{-3} emu when $H=200$ Oe. Figure 4(b) shows the coercivity H_c of $M-H$ curves as a function of the N . It was illustrated that the H_c decreased with increasing the N . The thickness of Bi:YIG thin film experimentally was estimated for each sample ($N=3, 5, 15$, and 20), based on the thickness of the Bi:YIG thin film (about 400 nm) and the M (9.3×10^{-4}

Fig. 6 The V_{SSE} as a function of the H for $\Delta T=1.7, 3.1, 4.6, 6.1, 7.5, 9.0$ K for each sample ((a) $N=3$, (b) $N=5$, (c) $N=10$, (d) $N=15$, and (e) $N=20$).

Fig. 7 ΔT dependence of the coercivity of V_{SSE} and the remanence of V_{SSE} for each sample ((a) $N=3$, (b) $N=5$, (c) $N=10$, (d) $N=15$, and (e) $N=20$). H_c of $M-H$ curve for each sample shown in Fig. 4 (b) are added with black dashed lines as to correspond to the scale of left vertical axis.

emu) of the sample ($N=10$). As a result, each thickness of Bi:YIG thin film was estimated at about 80, 190, 850, and 1100 nm, respectively.

Figure 5(a) shows the absolute temperature T dependence of $M-H$ curves for the sample ($N=10$) by using SQUID magnetometer in the range of 260K to 360K. Here, the M is normalized per unit volume of the Bi:YIG thin film. Figure 5(b) shows the coercivity H_c of $M-H$ curves as a function of the T . Figure 5(a) and (b) were illustrated the both M and H_c were changed no significant in the absolute temperature range in this measurement.

3.2 ΔT dependence of the V_{SSE}

ΔT dependence of the V_{SSE} was measured for each sample ($N = 3, 5, 10, 15$, and 20) with increasing ΔT . Figure 6 shows the V_{SSE} as a function of the H for $\Delta T=1.7, 3.1, 4.6, 6.1, 7.5, 9.0$ K. Here, the V_{SSE} when the H becomes zero is defined to the "remanence of V_{SSE} ", and the H when the V_{SSE} becomes zero is defined to the "coercivity of V_{SSE} ". It was illustrated that the remanence of V_{SSE} increases with increasing ΔT in the same sample, and also increase with increasing the N in the same ΔT . In the point of view of coercivity of V_{SSE} , it largely changed at the certain ΔT , except for the sample ($N=3$).

4. Discussion

Based on the above results, behaviors of the coercivity of V_{SSE} for the Bi:YIG/Pt device samples were discussed. Figures 7(a) to 7(e) show the ΔT dependence of the coercivity of the V_{SSE} and the remanence of V_{SSE} for each sample, in addition to the ΔT except for it shown in Fig. 6. From Fig. 7(a) to (e), it was shown that the coercivity of V_{SSE} largely changes in at the certain ΔT shown in the green region, except for the sample ($N=3$). Here, the ΔT shown in the green region is defined to " ΔT_g ", because it is the ΔT which the gap occurs in the coercivity of V_{SSE} . As shown in Fig. 7 (a) to (e), ΔT_g was decreased with the N increases. The H_c for each sample shown in Fig. 4 (b) is added with black dashed lines in Fig. 7(a) to (e), so as to correspond to the scale of left vertical axis. In this shown, when $\Delta T > \Delta T_g$, the coercivity of V_{SSE} was almost the same as the H_c for each sample. On the other hand, when $\Delta T < \Delta T_g$, the coercivity of V_{SSE} was about twice as the coercivity of V_{SSE} when $\Delta T > \Delta T_g$.

Figure 8 shows the coercivity of V_{SSE} as a function of the remanence of V_{SSE} for each sample. As mentioned above, it was shown that the ΔT depends on the N , however, it was shown that the remanence of V_{SSE} which the gap occurs in the coercivity of V_{SSE} is almost constant at about 290nV independently of the N . It is suggested that the large change in the coercivity of V_{SSE} may be due to the amount of spin current.

It is well known that the coercivity of V_{SSE} changes in samples which have different surface roughness of the ferromagnetic material, because the V_{SSE} reflects the magnetization information only near the interface^{5,6)}. In this paper, however, it is suggested that the large change

Fig. 8 The coercivity of V_{SSE} as a function of the remanence of V_{SSE} for each sample.

of the coercivity of V_{SSE} in the same sample by only ΔT is difference result, compared to above behavior depending on the surface roughness.

5. Conclusion

As a result of investigation of the temperature difference dependence of the spin Seebeck voltage (V_{SSE}) for the polycrystalline $\text{BiY}_2\text{Fe}_5\text{O}_{12}$ (Bi:YIG)/Pt device, it was shown that the coercivity of V_{SSE} largely changed at the certain temperature difference ΔT_g , and ΔT_g was decreased with the thickness of the Bi:YIG thin film increases. Focus attention on the remanence of V_{SSE} which the gap occurs in the coercivity of the V_{SSE} is almost constant independently of the thickness of Bi:YIG thin films. It is suggested that the large change in the

coercivity of V_{SSE} may be due to the amount of spin current.

Experimental studies of the spin Seebeck effect have mainly focused on improving magnitude of V_{SSE} per unit temperature difference and searching for new materials, and haven't been paid attention to the coercivity of V_{SSE} .

In this measurement, it is suggested that there is a discontinuous point in the coercivity of V_{SSE} which indicates that the direction of spin is hard to reverse in the spin current. The unique behavior of coercivity of V_{SSE} may be peculiar to polycrystalline Bi:YIG/Pt devices made by the metal organic decomposition method. In the future, it will be necessary to systematically investigation the process of the hysteresis loop of V_{SSE} at the spin Seebeck device based on polycrystalline ferromagnetic thin film to reveal the origin of this behavior.

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