Electric detection of the spin-Seebeck effect in Ni and Fe thin films at room temperature

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Abstract. The spin-Seebeck effects in Ni and Fe thin films have been investigated by using the inverse spin-Hall effect in a Pt film. The experimental results show that the sign of the spin-Seebeck coefficient for Ni is opposite to those for Fe and Ni$_{81}$Fe$_{19}$ and that the magnitude of the spin-Seebeck coefficients for Ni and Ni$_{81}$Fe$_{19}$ are much greater than that for Fe at room temperature. This material dependence of the spin-Seebeck coefficient is different from that of the conventional Seebeck coefficient.

1. Introduction
In the field of spintronics [1, 2], there have been many efforts to develop the generation methods of a spin current [3, 4], a flow of electron spin in a solid, for deriving magnetic devices. In this stream, the spin-Seebeck effect (SSE) was recently observed experimentally at room temperature [5]. SSE allows us to generate a pure spin current simply by placing a ferromagnetic metal in a temperature gradient [5-7].

In a ferromagnetic metal under a temperature gradient, the thermally generated spin current induces spin voltage $\mu_\uparrow - \mu_\downarrow$, where $\mu_\sigma$ is electrochemical potential for spin channel $\sigma$ ($\sigma = \uparrow$ or $\downarrow$). As shown in the previous work [5], the spin voltage $\mu_\uparrow - \mu_\downarrow$ induced from a uniform temperature gradient varies almost linearly along the temperature-gradient direction and the sign of $\mu_\uparrow - \mu_\downarrow$ is reversed between the opposite ends of the ferromagnet.

The spin voltage generated by SSE can be detected electrically by means of the inverse spin-Hall effect (ISHE) in a paramagnetic metal [8-19]. However, up to now, the SSE signal was reported only in a ferromagnetic Ni$_{81}$Fe$_{19}$ film. In this study, we measured the thermally induced spin voltage in ferromagnetic Ni and Fe thin films by using ISHE of a Pt film.

2. Methods
Figure 1(c) is a schematic illustration of the sample system used in the present study. The sample consists of a 20-nm-thick ferromagnetic (Ni or Fe) film with a 10-nm-thick Pt wire attached to one end. The lengths of the ferromagnetic layer and the Pt wire along the $x$ ($y$) direction are 6 mm (4 mm) and 0.1 mm (4 mm), respectively. The ferromagnetic layer was deposited on the sapphire substrate by electron-beam evaporation in a high vacuum, and then
the Pt wire was sputtered on the end of the ferromagnetic layer in an Ar atmosphere. We apply an in-plane magnetic field, \( \mathbf{H} \), with magnitude \( H \) along the \( x \) direction (see figures 1(c) and 1(d)). A uniform temperature gradient \( \nabla T \) is applied along the \( x \) direction. The uniformity of \( \nabla T \) in the ferromagnetic layer was confirmed by measuring thermoelectric voltage along the \( x \) direction.

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V_{\text{ISHE}} \equiv E_{\text{ISHE}} L_{\text{Pt}} = -\frac{\theta_{\text{Pt}} \eta_{\text{F/Pt}}}{e} \left( \frac{L_{\text{Pt}}}{d_{\text{Pt}}} \right) (\mu_{\uparrow} - \mu_{\downarrow}),
\]

where \( E_{\text{ISHE}} \) is the magnitude of \( \mathbf{E}_{\text{ISHE}} \), \( \theta_{\text{Pt}} \) is the spin-Hall angle in Pt \([18]\), \( \eta_{\text{F/Pt}} \) is the spin-injection efficiency \([4]\) across the F(Ni or Fe)/Pt interface, \( d_{\text{Pt}} \) is the thickness of the Pt wire, and \( L_{\text{Pt}} \) is the length of the Pt wire along the \( y \) direction. We measured the electric voltage difference \( V \) between the ends of the Pt wire to detect the \( V_{\text{ISHE}} \) signal, when the Pt wire is on the higher- and lower-temperature ends of the sample, as illustrated in figures 1(c) and 1(d).

3. Results and Discussion

Figures 2(a) and 2(c) show the measured voltage \( V \) as a function of the temperature difference between the ends of the sample, \( \Delta T \), when the Pt wire is on the higher- and lower-temperature ends of the Ni/Pt and Fe/Pt samples, respectively. In each sample, the magnitude of \( V \) is proportional to \( \Delta T \) and the sign of \( V \) for finite values of \( \Delta T \) is clearly reversed between the ends of the sample. This behavior of \( V \) is consistent with the feature of ISHE induced by SSE.

As shown in figures 2(b) and 2(d), these \( V \) signals disappear in plain Ni and Fe films in which the Pt wires are absent. These results show that these signals are irrelevant to the anomalous Nernst-Ettingshausen effects \([21]\) in the ferromagnetic layers, and the temperature gradient along the \( z \) direction is absent in the ferromagnets.

In figures 3(a) and 3(b), we show \( V \) as a function of \( H \) for various values of \( \Delta T \), measured in the Ni/Pt and Fe/Pt samples, respectively. The signs of \( V \) at each end of the samples are
reversed by reversing $H$. On the basis, these $V$ signals observed are attributed to the ISHE voltage induced by SSE, $V_{\text{ISHE}}$.

In table 1, we show the values of the ISHE voltage at the higher-temperature end of the sample, $V_{\text{ISHE,HT}}$, for the Ni/Pt, Fe/Pt, and Ni$_{81}$Fe$_{19}$/Pt sample systems. The data for the Ni$_{81}$Fe$_{19}$/Pt sample is cited from Ref. [5]. Table 1 shows that the sign of $V_{\text{ISHE}}$ for the Ni/Pt sample is opposite to those for the Fe/Pt and Ni$_{81}$Fe$_{19}$/Pt [5] samples, and the sign of the thermally generated spin voltage in Ni is also opposite to those in Fe and Ni$_{81}$Fe$_{19}$ at room temperature. Using equation (1) and the experimental values of $V_{\text{ISHE,HT}}$, we estimated the values of the thermally generated spin voltage at the higher-temperature end, $(\mu_\uparrow - \mu_\downarrow)_{\text{HT}}$, and the spin-Seebeck coefficients $S_s \equiv (2/e)((\mu_\uparrow - \mu_\downarrow)_{\text{HT}}/\Delta T)$ of the ferromagnets (see table 1). Notable is that the signs and the orders of the magnitude of $S_s$ for Ni, Fe, and Ni$_{81}$Fe$_{19}$ are distinctly different from those of the conventional Seebeck coefficients, $S$ (see also table 1). This
shows that the origin of SSE is different from that of the conventional Seebeck effect.

**Table 1.** Comparison of $S_s$ and $S$ for the Ni, Fe, and Ni$_{81}$Fe$_{19}$ films. The values of $V_{\text{SHE,HT}}/\Delta T$ are estimated from the data shown in figure 2 and Ref. [5]. $\eta_F/\eta_{Pt}$ is calculated by using the phenomenological theory in Ref. [4]. For calculating $S_s$, $\theta_{Pt} = 0.08$ is used [18].

| Material        | $V_{\text{SHE,HT}}/\Delta T$ (V/K) | $\eta_F/\eta_{Pt}$ | $S_s$ (V/K) | $S$ (V/K) |
|-----------------|-----------------------------------|---------------------|-------------|-----------|
| Ni              | $-1.20 \times 10^{-7}$            | 0.16                | $5 \times 10^{-11}$ | $-15 \times 10^{-6}$ |
| Fe              | $0.21 \times 10^{-7}$             | 0.18                | $-0.7 \times 10^{-11}$ | $5 \times 10^{-6}$ |
| Ni$_{81}$Fe$_{19}$[5] | $2.60 \times 10^{-7}$            | 0.27                | $-6 \times 10^{-11}$ | $-20 \times 10^{-6}$ |

**4. Conclusion**

We have measured the thermally induced spin voltage in Ni and Fe thin films by using the inverse spin-Hall effect in a Pt wire, and estimated the spin-Seebeck coefficient for Ni, Fe, and Ni$_{81}$Fe$_{19}$ at room temperature from the measured spin voltage. The experimental results show that the sign of the spin-Seebeck coefficient for Ni is opposite to those for Fe and Ni$_{81}$Fe$_{19}$. We compared the spin-Seebeck coefficients with the conventional Seebeck coefficients and concluded the origin of the thermally induced spin voltage is different from that of the conventional Seebeck effect.

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