Spin Peltier effect and its length scale in Pt/YIG system at high temperatures

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In recent years, the field of spin caloritronics has been rapidly developing by involving thermal effects in spintronics. In this field, various magneto-thermoelectric and thermo-spin effects unique to magnetic and spintronic materials have been discovered and investigated. Representative thermo-spin effects are the spin Seebeck effect (SSE) and its reciprocal called the spin Peltier effect (SPE) appearing in metal/magnetic-insulator junction systems. SPE is the generation of a spin (heat) current from a heat (spin) current, where the spin current is carried by magnons in the magnetic insulator. In combination with the inverse (direct) spin Hall effect, SSE (SPE) enables transverse heat-to-charge (charge-to-heat) current conversion in simple insulator-based systems. Because of their intriguing mechanism and technological advantages, SSE and SPE have attracted attention as next-generation energy harvesting and thermal management principles for spintronic devices, respectively.

In order to clarify the physical mechanism of SSE and SPE, their temperature $T$, magnetic field $H$, and thickness dependences have been investigated systematically using the lock-in thermography method. The obtained systematic dataset will help to elucidate the detailed mechanisms of SSE and SPE.

Figure 1(a) shows the schematic illustration of the sample used in this paper. The sample consists of a Pt strip with a thickness of 5 nm and width of 0.4 mm sputtered on an YIG/gadolinium gallium garnet (Gd$_3$Ga$_5$O$_{12}$: GGG) substrate with the YIG thickness gradient $t_{YIG}$. The substrate with $t_{YIG}$ was prepared by obliquely polishing a 25 μm thick single-crystalline YIG (111) grown on a 0.5 mm thick single-crystalline GGG (111) substrate by a liquid phase epitaxy method. The obtained $t_{YIG}$ was confirmed to be 6.4 μm mm$^{-1}$ by a cross-sectional scanning electron microscopy [Fig. 1(c)]. In order to investigate the $T$ dependence, the sample was fixed on a stage with a heater and a temperature sensor by heat-resistant adhesive (Aron Ceramic D, Toagosei Co., Ltd.). Conducting wires were electrically connected to the ends of the Pt strip using heat-resistant conductive paste (MAX102, Nihon Handa Co., Ltd.). An insulating black ink was coated on the sample surface to increase the infrared emissivity and to make the emissivity uniform. To degas the sample and stage, they were heated up to 600 K for an hour in a high vacuum before the measurement. The electrical resistivity of the Pt strip was unchanged after heating and its $T$ dependence was similar to that obtained in a previous study.

We measured the SPE-induced temperature change by using the LIT method [Fig. 1(d)]. A square-wave-modulated AC charge current with the amplitude of $J_0=5$ mA, frequency of $f = 5$ Hz, and zero offset was applied to the Pt strip. To align the magnetization of YIG, an in-plane magnetic field $H$ with the magnitude $\mu_0|H| = 100$ mT was applied along the $x$ direction, where $\mu_0$ is the vacuum

The temperature and yttrium-iron-garnet (YIG) thickness dependences of the spin Peltier effect (SPE) have been investigated using a Pt/YIG junction system at temperatures ranging from room temperature to the Curie temperature of YIG by the lock-in thermography method. By analyzing the YIG thickness dependence using an exponential decay model, the characteristic length of SPE in YIG is estimated to be 0.9 μm near room temperature and almost constant even near the Curie temperature. The high-temperature behavior of SPE is clearly different from that of the spin Seebeck effect, providing a clue for microscopically understanding the reciprocal relation between them.

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above the line, no SPE signal should be generated above room temperature because of the absence of YIG. The area surrounded by an orange dotted rectangle shows the position and size of the Pt strip. Based on the $\nu_{\text{YIG}}$ value, the $\nu_{\text{YIG}}$ resolution in our setup was obtained to be 30 nm/pixel. During the LIT measurements, the temperature of the sample surface was monitored with the infrared camera in a high vacuum of $<4 \times 10^{-4}$ Pa through a CaF$_2$ window with high infrared transparency. The small reduction of the infrared emission intensity from the sample due to the CaF$_2$ window was corrected based on a calibration curve, which was measured by using a resistance temperature sensor as a dummy sample and by comparing the sensor and thermal image values.

Figures 2(a) and 2(b) show the $A_{\text{odd}}$ and $\phi_{\text{odd}}$ images for the Pt/wedged-YIG sample at $T = 314$ K. The current-induced temperature change appears only in the region with the Pt strip on the YIG film. Since $A_{\text{odd}}$ and $\phi_{\text{odd}}$ are the $H$-odd components, the contribution from the field-independent Peltier effect is eliminated. The magnitude ($A_{\text{odd}}$) and sign ($\phi_{\text{odd}}$) of the observed temperature modulation is consistent with the SPE signal reported previously in the Pt/YIG systems.\(^{24}\) Importantly, the observed temperature modulation appears only in the vicinity of the Pt/YIG junction and does not broaden in the lateral direction. These features indicate that this temperature change is due to SPE. We also found that no temperature modulation is generated in the region without YIG, confirming that the ordinary Ettingshausen effect in Pt is negligibly small. Figures 2(c) and 2(d) show the profile of the $A_{\text{odd}}$ and $\phi_{\text{odd}}$ signals in the $y$ direction. In the region with finite $\nu_{\text{YIG}}$, the SPE signal monotonically increases with increasing $\nu_{\text{YIG}}$ and saturates when $\nu_{\text{YIG}} > 5 \mu$m. The spatial distribution of the SPE signal is also consistent with the previous result.\(^ {24}\)

Figures 3(a) and 3(b) show the $A_{\text{odd}}$ and $\phi_{\text{odd}}$ images for various values of $T$ in the high-temperature range. The images show that the SPE signal disappears at 552 K, around

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**Fig. 1.** (Color online) (a) Schematic of the Pt/wedged-YIG system used for the SPE measurement. The YIG film has a thickness gradient $V_{\nu_{\text{YIG}}}$ along the $y$ direction. (b) Steady-state infrared image of the Pt/wedged-YIG system. The area below the white dotted line corresponds to the area with the finite YIG thickness $t_{\text{YIG}}$. The area surrounded by the orange dotted rectangle corresponds to the area with the Pt film. (c) $V_{\nu_{\text{YIG}}}$ profile and cross-sectional image of the wedged-YIG/GGG substrate without the Pt layer, measured by scanning electron microscopy. The samples used for the SPE and scanning electron microscopy measurements were cut from the same wafer. (d) Schematic of the LIT method for measuring SPE. The base temperature $T$ of the sample was controlled by a heater attached to the stage and monitored with an infrared camera.

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permeability. When the charge current is applied to the Pt strip, a spin current is generated by the spin Hall effect.\(^ {8,9}\) This spin current is injected into YIG at the Pt/YIG interface, causing the temperature change induced by SPE $\Delta T_{\text{SPE}}$ when the charge current direction is perpendicular to the magnetization of YIG.\(^ {6,7,17}\) The SPE-induced temperature change is known to be localized in the vicinity of the Pt/YIG interface owing to the formation of dipolar heat sources, allowing us to investigate the $\nu_{\text{YIG}}$ dependence of $\Delta T_{\text{SPE}}$ without being affected by lateral temperature broadening.\(^ {6,7,17}\) As demonstrated in the previous studies, $\Delta T_{\text{SPE}}$ can be detected by the LIT method because $\Delta T_{\text{SPE}}$ changes its sign depending on the charge current direction.\(^ {6,7,17,24}\) The first-harmonic component of the temperature oscillation was extracted from thermal images taken with an infrared camera by Fourier analysis and converted into the lock-in amplitude $A$ and phase $\phi$ images. Since $\Delta T_{\text{SPE}}$ shows the $H$-odd dependence, we calculated $A_{\text{odd}} = |A(+H)e^{-i\phi_{\text{odd}}}-A(-H)e^{i\phi_{\text{odd}}}|/2$ and $\phi_{\text{odd}} = -\text{arg}[A(+H)e^{-i\phi_{\text{odd}}}-A(-H)e^{i\phi_{\text{odd}}}]$ from the thermal images measured with applying positive and negative magnetic fields. The SPE-induced temperature change was obtained by $\Delta T_{\text{SPE}} = A_{\text{odd}}\cos\phi_{\text{odd}}$ since the time delay due to thermal diffusion is negligibly small in the LIT-based SPE measurements.\(^ {6,7,17,19}\) Figure 1(b) shows a steady-state infrared image of the black-ink-coated sample at 314 K, where the YIG film with $V_{\nu_{\text{YIG}}}$ exists below the white dotted line. In the region
dependence of $\nabla$ the positions of the white dotted lines depicted in the rightmost shows the.*

where $T_c$ of YIG [note that the electrical resistivity of the Pt strip exhibits no anomaly around $T_c$, as shown in the inset to Fig. 3(c)]. The $T$ dependence of $\Delta T_{\text{SPE}}$ at each $T_{\text{YIG}}$ was calculated by averaging the $A_{\text{odd}}$ and $\phi_{\text{odd}}$ data along the $x$ direction over a length of 0.4 mm. At $T_{\text{YIG}} = 5.00 \mu m$, where the SPE signal reaches the saturation value, the magnitude of the SPE signal is almost constant up to 400 K but monotonically decreases with increasing $T$ for $T > 400$ K [Fig. 3(c)]. The similar $T$ dependence of $\Delta T_{\text{SPE}}$ was obtained also in the small $T_{\text{YIG}}$ region in which the SPE signal does not saturate.

To investigate the $T$ dependence of the characteristic length of SPE in YIG, we analyzed the $T_{\text{YIG}}$ dependence of the SPE signal at each temperature. Here, we adopt a simple phenomenological exponential decay model with a minimum fitting parameter $l_{\text{SPE}}$:

$$\Delta T_{\text{SPE}} \propto 1 - \exp\left(-\frac{T_{\text{YIG}}}{l_{\text{SPE}}}\right).$$

(1)

where $l_{\text{SPE}}$ is the characteristic length of SPE, i.e. the propagation length of nonequilibrium magnons in YIG that contribute to SPE. Figure 4(a) shows the experimental and fitting results for various values of $T$. When the SPE signal is sufficiently large, the experimental results are well fitted by Eq. (1) in the whole thickness range, where the coefficient of determination is $R^2 > 0.8$ for $T < 520$ K. However, for $T > 520$ K, the fitting accuracy is poor ($R^2 < 0.8$) in the small $T_{\text{YIG}}$ region because of the small magnitude of the SPE signal. Figure 4(b) shows the $T$ dependence of $l_{\text{SPE}}$ and $R^2$. The $l_{\text{SPE}}$ value near room temperature ($314 \text{ K}$) is estimated to be 0.9 $\mu m$, which is comparable to the values obtained in the previous studies on SPE.24,26,27 We found that $l_{\text{SPE}}$ remains almost constant as the temperature increases.

Next, we compare the $T$ dependence of the SPE signal with that of the SSE voltage. If the reciprocal relation between SPE and SSE and $T$-independent $l_{\text{SPE}}$ are assumed, the SSE voltage normalized by the applied temperature difference can be compared with the factor proportional to $(\kappa/T)(\Delta T_{\text{SPE}}/j_c)$, where $\kappa$ is the thermal conductivity of YIG.20 Figure 4(c) shows the $(\kappa/T)(\Delta T_{\text{SPE}}/j_c)$ values as a function of $T$ at $T_{\text{YIG}} = 5.00 \mu m$, where the $T$ dependence of $\kappa$ is estimated from the data in Ref. 21. The magnitude of $(\kappa/T)(\Delta T_{\text{SPE}}/j_c)$ almost linearly decreases with increasing $T$, which is different from the behavior of the SSE voltage.21 In order to quantify the $T$ dependence of SPE, $(\kappa/T)(\Delta T_{\text{SPE}}/j_c)$ is fitted by

$$\frac{\kappa}{T} \frac{\Delta T_{\text{SPE}}}{j_c} \propto (T_c - T)^\beta.$$  

(2)

The $(\kappa/T)(\Delta T_{\text{SPE}}/j_c)$ data is well fitted with the critical exponent of $\beta = 1.1$ [Fig. 4(c)]. We observed the same $T$ dependence of the SPE signal with $\beta = 1.1$ also in a Pt-film/ YIG-slab junction system with the single-crystalline YIG slabs grown by a flux method. This result is clearly different from the $T$ dependence and $T$ dependence and characteristic length of these phenomena can be different from each other. In fact, the previous SSE experiments showed that the characteristc length for SSE in Pt/YIG...
systems varies in the range of 1–10 μm depending on the measurement configuration and method to apply a temperature gradient.15,26–33 This situation indicates that the Onsager reciprocal relation between SPE and SSE is not simple and its magnon-frequency dependence should be taken into account. To clarify the spectral nature of SPE, in addition to the T and T dependence of the SPE signal in the Pt/YIG system was found to monotonically decrease with increasing T when T > 400 K and disappear around the Curie temperature of YIG. By fitting the observed dependence of the SPE signal by the exponential decay model, the characteristic length of SPE was estimated to be 0.9 μm near room temperature (314 K) and be almost constant as the temperature increases. The SPE-related factor that can be compared with the SSE voltage, (dT/T)dSPE, shows the (Tc – T) dependence, which is significantly different from the T dependence of the SSE voltage in the Pt/YIG system: (Tc – T)α with α = 1.5–3.0. The results reported here highlight the difference in the thermo-spin conversion between SPE and SSE and suggest the magnon-frequency-dependent nature in the reciprocal relation between them.

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Fig. 4. (Color online) (a) τVG dependence of ΔTSTR (blue) and fitting curves (orange) for various values of T at μH/Hz = 100 mT and J = 5 mA. (b) T dependence of the characteristic length of SPE, ΔTSPE (orange) and coefficient of determination of the fitting R2 (green), obtained by fitting the τVG dependence of ΔTSTR; at each temperature with Eq. (1). (c) T dependence of (dT/T)dSPE, where k and j are the thermal conductivity of YIG and charge current density, respectively. The T dependence of k is estimated from the data in Ref. 21. The green line shows the fitting results using Eq. (2).

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