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Electric detection of the spin-Seebeck effect in magnetic insulator in the presence of interface barrier

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Abstract. The spin-Seebeck effect (SSE), the spin-voltage generation as a result of a temperature gradient, has recently been observed in ferrimagnetic insulator $LaY_2Fe_5O_{12}$ films by means of the inverse spin-Hall effect in Pt films. Here we investigate the SSE using $LaY_2Fe_5O_{12}/SiO_2$(Cu)/Pt systems, where the $LaY_2Fe_5O_{12}$ and Pt layers are separated by SiO_2 (Cu) thin-film barriers. The experimental results show that the SSE signal disappears in the $LaY_2Fe_5O_{12}/SiO_2$/Pt system, but the finite signal appears in the $LaY_2Fe_5O_{12}$/Cu/Pt system, indicating that the direct contacts between the $LaY_2Fe_5O_{12}$ and normal metals is necessary for generating the SSE signal.

In the fields of spintronics [1, 2] and spin caloritronics [3], spin-voltage generation from heat is highly desired for driving spin-based devices and for enhancing their efficiency. Here, spin voltage refers to the potential for electron's spins, which drives a spin current, i.e., a flow of spin angular momentum [4-6]. The spin-Seebeck effect (SSE) is one enabling the generation, which converts a heat current into the spin voltage in ferromagnetic metals [7-9], semiconductors [10], and insulators [11]. The SSE was recently observed in a garnet-type ferrimagnetic insulator $LaY_2Fe_5O_{12}$ film by means of the inverse spin-Hall effect (ISHE) [12-19] in Pt films attached on the $LaY_2Fe_5O_{12}$ [11]. In this paper, to buttress the previous results on the SSE in the $LaY_2Fe_5O_{12}$/Pt systems, we report supplementary experiments using $LaY_2Fe_5O_{12}/SiO_2$/Pt and $LaY_2Fe_5O_{12}$/Cu/Pt systems. The experiments show that the direct contacts between $LaY_2Fe_5O_{12}$ and normal metals is necessary for the SSE experiments.

Figure 1 schematically shows the experimental setup for measuring the SSE-induced ISHE. The device consists of a rectangular-shaped ferromagnet (F) with two (or more) normal-metal (N) wires attached on the top of the F layer, where F and N correspond to $LaY_2Fe_5O_{12}$ and Pt in the previous experiments, respectively [11]. Here, an in-plane temperature gradient ∇T is applied to the F layer along the x direction (see figure 1). Since the localized magnetic moments in F and conduction electrons in N are coupled by the interface spin-exchange interaction, or spin-mixing conductance [20, 21], the thermally generated spin voltage injects a spin current into the N wire with a spatial direction $\mathbf{J}_s$ (z direction) and a spin-polarization vector $\boldsymbol{\sigma}$ parallel to the magnetization $\mathbf{M}$ direction of the F layer (x direction). In the N layer, this spin current is converted into an electric field $\mathbf{E}_{\text{ISHE}}$ due to the ISHE. When $\mathbf{M}$ is along the ∇T direction, $\mathbf{E}_{\text{ISHE}}$ is generated along the N layer (y direction) because of the relation $\mathbf{E}_{\text{ISHE}} \propto \mathbf{J}_s \times \boldsymbol{\sigma}$

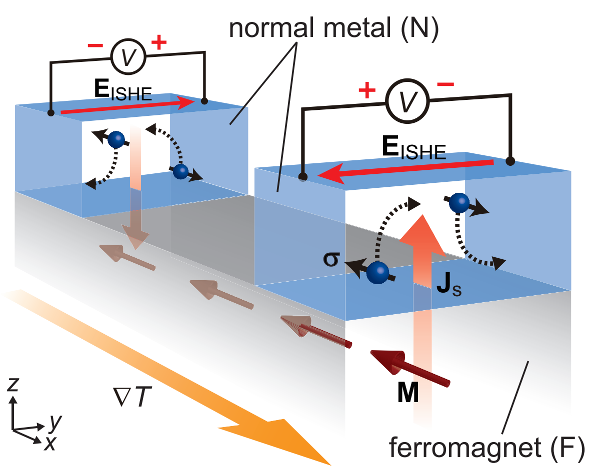

Figure 1. A schematic illustration of the spin-Seebeck effect (SSE) in a ferromagnet (F) and the inverse spin-Hall effect (ISHE) in normal metals (Ns). Here, $\mathbf{M}$, $\mathbf{J}_s$, and $\mathbf{E}_{\mathrm{ISHE}}$ denote the magnetization vector of the F layer, the spatial direction of the spin current, and the electric field generated by the ISHE in the N layer, respectively. In Ref. [11], $LaY_2Fe_5O_{12}$ and Pt films were used as the F and N layers, respectively. While $LaY_2Fe_5O_{12}$ is a ferrimagnet, it behaves like a ferromagnet under the present experimental conditions [11].

[12]. Therefore, by measuring $\mathbf{E}_{\mathrm{ISHE}}$, we can detect the SSE in the F layer electrically. Since the sign of the spin voltage generated by the SSE is reversed between the higher- and lower-temperature ends of the F layer, the sign of $\mathbf{E}_{\mathrm{ISHE}}$ is also reversed between the ends of the F/N device (see figure 1) [11, 21]. In this setup, collinear orientation of the temperature gradient and magnetization suppresses experimental artifacts with the same symmetry as the Nernst-Ettingshausen effect [22]. The following supplementary experiments further support the above interpretation on the SSE measurements.

In the present study, in addition to the conventional $LaY_2Fe_5O_{12}$/Pt sample, we fabricated $LaY_2Fe_5O_{12}/SiO_2$/Pt and $LaY_2Fe_5O_{12}$/Cu/Pt systems, where the $LaY_2Fe_5O_{12}$ and Pt layers are separated by thin SiO_2 and Cu films, respectively. First, the single-crystal $LaY_2Fe_5O_{12}$ (111) film with the 8×4 mm^2 rectangular shape and 3.9 μm thickness was grown on a $Gd_3Ga_5O_{12}$ (111) substrate by liquid phase epitaxy. Then, the two 10-nm-thick SiO_2 (12-nm-thick Cu) wires were fabricated on the $LaY_2Fe_5O_{12}$ layer by a sputtering (an electron-beam evaporation) method. Finally, the Pt films were sputtered on the SiO_2 (Cu) wires. The thickness of the Pt wires is 15 nm (10 nm) for the $LaY_2Fe_5O_{12}/SiO_2$(Cu)/Pt sample. The length and width of the Pt, SiO_2, and Cu wires are 4 mm and 0.1 mm, respectively. An in-plane external magnetic field H and a uniform ∇T were applied along the x direction (see figure 2). Here, the temperatures of both the ends of the sample were stabilized to 300 K and $300\,\mathrm{K} + \Delta T$, where the temperature difference ΔT was fixed at 20 K. We measured electric voltage difference V between the ends of the Pt layer of each sample using a micro probing system.

Figure 2(a) shows the measured voltage V as a function of H in the $LaY_2Fe_5O_{12}$/Pt sample at $\Delta T = 20\,\mathrm{K}$, measured when the probe needles are attached to the ends of the Pt layer placed at the higher-temperature end of the sample. By reversing H, the finite voltage step appears; the sign of V is reversed in response to the magnetization reversal of the $LaY_2Fe_5O_{12}$ layer. This situation is consistent with the feature of the ISHE induced by the SSE. In Ref. [11], we confirmed that the results of the ΔT dependent and Pt-wire-position dependent measurements are also consistent with the SSE behavior.

Figure 2(b) shows the H dependence of V at $\Delta T = 20\,\mathrm{K}$ in the $LaY_2Fe_5O_{12}/SiO_2$/Pt sample. In this sample, the V signal completely disappears (see also the inset in figure 2(b)). In contrast, in the $LaY_2Fe_5O_{12}$/Cu/Pt sample, the small but finite V signal appears although the Cu layers are thicker than the SiO_2 layers (see the inset in figure 2(c)), indicating that the V signals in figures 2(a) and 2(c) are attributed to the direct contact and thermally activated interface spin exchange between the $LaY_2Fe_5O_{12}$ and normal metals [11, 21]. The results in figures 2(b) and 2(c) also become evidence that the Pt layers in the samples are not magnetized by the proximity

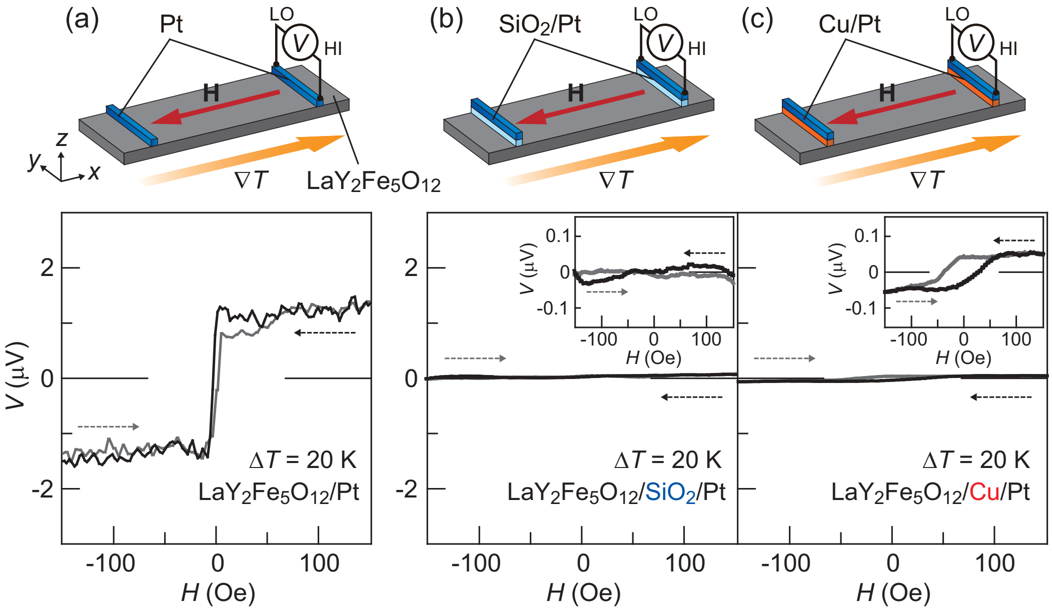

Figure 2. H dependences of V in the $LaY_2Fe_5O_{12}$(3.9 μm)/Pt(15 nm) sample (a), the $LaY_2Fe_5O_{12}$(3.9 μm)/SiO_2(10 nm)/Pt(15 nm) sample (b), and the $LaY_2Fe_5O_{12}$(3.9 μm)/Cu(12 nm)/Pt(10 nm) sample (c) at $\Delta T = 20$ K. Here, a parenthetic number represents the thickness of each layer. The insets in (b) and (c) show the H dependences of V in the $LaY_2Fe_5O_{12}/SiO_2$/Pt and $LaY_2Fe_5O_{12}$/Cu/Pt samples at $\Delta T = 20$ K in which the vertical axes are magnified. All the results were measured in the Pt wires attached to the higher-temperature ends of the sample. The differences of the noise levels and coercive forces between the data in (a) and (c) are due to those of the smoothing parameters. The V-H curve in (a) reflects the actual magnetization curve of the $LaY_2Fe_5O_{12}$ layer (see Ref. [11]).

effect from the $LaY_2Fe_5O_{12}$ interface. Therefore, we can conclude that the V signals are due entirely to the SSE in the magnetic insulator $LaY_2Fe_5O_{12}$.

In summary, to buttress our previous experiments [11], we have investigated the spin-Seebeck effect (SSE) in the ferrimagnetic insulator $LaY_2Fe_5O_{12}$ films with the SiO_2/Pt and Cu/Pt wires. Although the inverse spin-Hall voltage induced by the SSE disappears in the $LaY_2Fe_5O_{12}/SiO_2$/Pt sample, the finite signal appears in the $LaY_2Fe_5O_{12}$/Cu/Pt system. These results confirm that the observed V signals are attributed to the ISHE induced from the thermally generated spin voltage in the $LaY_2Fe_5O_{12}$ layer.

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