Critical suppression of spin Seebeck effect by magnetic fields

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The longitudinal spin Seebeck effect (LSSE) in Pt/Y3Fe2O12 (YIG) junction systems has been investigated at various magnetic fields and temperatures. We found that the LSSE voltage in a Pt/YIG-slab system is suppressed by applying high magnetic fields and this suppression is critically enhanced at low temperatures. The field-induced suppression of the LSSE in the Pt/YIG-slab system is too large at around room temperature to be explained simply by considering the effect of the Zeeman gap in magnon excitation. This result requires us to introduce magnon-frequency-dependent mechanism into the scenario of LSSE; low-frequency magnons dominantly contribute to the LSSE. The magnetic field dependence of the LSSE voltage was observed to change by changing the thickness of YIG, suggesting that the thermo-spin conversion by the low-frequency magnons is suppressed in thin YIG films due to the long characteristic lengths of such magnons.

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I. INTRODUCTION

Magnons are collective excitations of spins in magnetic ordered states, the concept of which was first introduced by Bloch in order to explain the temperature dependence of magnetization in a ferromagnet. In thermal equilibrium states, magnons behave as weakly interacting bosonic quasiparticles obeying the Bose-Einstein distribution:

$$f_{BE}(\epsilon, T_m) = \frac{1}{\exp(\epsilon/k_B T_m) - 1},$$  (1)

where $\epsilon$ is the magnon energy, $k_B$ is the Boltzmann constant, and $T_m$ is the magnon temperature. In soft magnetic materials such as Y3Fe2O12 (YIG), magnons are easily excited by thermal energy since the magnon dispersion is almost gapless except for a small gap due to the Zeeman effect and magnetic anisotropy ($\sim 10^{-3}$ K for YIG [3, 4]).

In the field of spintronics [5, 6], magnons have attracted renewed attention, since they can carry a spin current without accompanying a charge current [7, 8]. Importantly, a magnon spin current in a magnet can interact with a conduction-electron spin current in an attached metal at the metal/magnet interface via the interface exchange interaction, which is described in terms of the spin-mixing conductance [3, 11]. By making use of this interaction, various spin-current-related phenomena have been developed, such as the spin pumping [8, 12, 13], spin Seebeck effect (SSE) [14, 37], and their reciprocal effects [8, 38].

The SSE refers to the generation of a spin current as a result of a temperature gradient in a magnetic material. Here, the thermally generated spin current is detected as electric voltage (SSE voltage) via the inverse spin Hall effect (ISHE) [12, 13, 39, 41] in a paramagnetic metal attached to a magnet. The observation of the SSE in a ferrimagnetic insulator YIG [13, 17] implies that this phenomenon is attributed to nonequilibrium magnon dynamics driven by a temperature gradient, since a conduction electrons’ contribution in YIG is frozen out due to its large charge gap. After the pioneering theoretical work by Xiao et al. [42], the SSE is mainly described in terms of the effective magnon temperature $T_m$ in a ferrimagnet and effective electron temperature $T_e$ in an attached paramagnetic metal; when the effective magnon-electron temperature difference is induced by an external temperature gradient, a spin current is generated across the ferrimagnet/paramagnet interface. Adachi et al. developed linear-response theories of the magnon- and phonon-mediated SSEs [13, 43, 45]. Subsequently, Hoffman et al. formulated a Landau-Lifshitz-Gilbert theory of the SSE to investigate the thickness dependence and length scale of the SSE [46]. In 2014, Rezende et al. discussed the SSE in terms of a bulk magnon spin current created by a temperature gradient in a ferrimagnetic insulator [31]. However, microscopic understanding of the relation between the magnon excitation and thermally generated spin currents is yet to be established, and more systematic experimental studies are necessary.

A clue to understand a role of magnons in SSE already manifested itself in magnetic-field-dependence measurements. In Ref. 29, we showed that the magnitude of the SSE voltage in paramagnetic-metal (Pt, Au)/YIG-slab junction systems gradually decreases with increasing the magnetic field after taking its maximum value at room temperature [see Fig. 1(b)]. This suppression of
the SSE voltage becomes apparent by applying high magnetic fields, while it is very small in the conventional SSE measurements in a low field range [see Fig. 1(c)]. The LSSE suppression by high magnetic fields is irrelevant to the anomalous Nernst effect due to static proximity ferromagnetism in Pt [17], since the same behavior was observed not only in Pt/YIG-slab systems but also in Au/YIG-slab systems [29] (note that Au is free from the proximity ferromagnetism). Although this result implies that the SSE is affected by a magnon gap opening due to the Zeeman effect, there was no detailed discussion on the high-magnetic-field behavior of the SSE. In this study, using Pt/YIG systems, we systematically investigated effects of high magnetic fields on the SSE at various temperatures ranging from 300 K to 5 K. We also report the YIG-thickness dependence of the SSE voltage and its suppression at high magnetic fields. The results suggest an important role of excitation of low-frequency magnons and an important step in unraveling the nature of the SSE.

II. EXPERIMENTAL CONFIGURATION AND PROCEDURE

Experiments on the SSE have been performed mainly in a longitudinal configuration owing to its simplicity [17, 20, 37], and we also employ this configuration in this study. Figure 1(a) shows a schematic illustration of the longitudinal SSE (LSSE). In the longitudinal configuration, when a temperature gradient, \( \nabla T \), is applied to a paramagnetic-metal/ferrimagnetic-insulator junction system perpendicular to the interface, a spin current is thermally generated in the paramagnetic layer along the \( \nabla T \) direction. The spin current is converted into an electric field \( E_{\text{ISHE}} \) by the ISHE in the paramagnetic layer if the spin-orbit interaction of the paramagnet is strong [see Fig. 1(a)]. When the magnetization \( M \) of the ferrimagnet is along the \( x \) direction, \( E_{\text{ISHE}} \) is generated in the paramagnet along the \( y \) direction following

\[
E_{\text{ISHE}} = (\theta_{\text{SH}} \rho) J_s \times \sigma,
\]

where \( \theta_{\text{SH}} \), \( \rho \), \( J_s \), and \( \sigma \) are the spin Hall angle, electric resistivity, spatial direction of a spin current, and spin-polarization vector of electrons in the paramagnet, respectively. Therefore, the LSSE can be detected electrically by measuring electric voltage \( V_{\text{ISHE}} = E_{\text{ISHE}} L_y \) in the paramagnetic metal layer, where \( E_{\text{ISHE}} \) is the magnitude of \( E_{\text{ISHE}} \) and \( L_y \) is the length of the paramagnetic layer along the \( y \) direction.

To investigate the high-magnetic-field behavior of the LSSE, we used Pt/YIG junction systems, which are now recognized as a model system for studying spin-current physics [8, 15]. The sample used in the present study consists of a 5-nm-thick Pt film sputtered on the whole of the (111) surface of a single-crystalline YIG slab or film. The YIG slab has no substrate, of which the lengths along the \( x \), \( y \), and \( z \) directions are \( L_x = 2.0 \) mm, \( L_y = 4.0 \) mm, and \( L_z = 1.0 \) mm, respectively. To measure the thickness dependence of the LSSE, we prepared three YIG films with the thicknesses of \( t_{\text{YIG}} = 10.42 \mu \text{m}, 1.09 \mu \text{m}, \) and \( 0.31 \mu \text{m} \), grown on the whole of single-crystalline Gd\(_3\)Ga\(_5\)O\(_{12}\) (GGG) (111) substrates by a liquid phase epitaxy method. The GGG substrates with the YIG films were then cut into a rectangular shape with the size of \( L_x = 2.0 \) mm, \( L_y = 4.0 \) mm, and \( L_z = 0.5 \) mm. To apply \( \nabla T \), the sample was sandwiched between two sapphire plates (1) and (2). The sapphire (1) is thermally connected to a heat bath of which the temperature \( T \) was controlled and varied in the range from 300 K to 5 K. By applying a charge current to a chip heater attached on the top of the sapphire (2), its temperature is increased. To improve the thermal contact, thermal grease was applied between the sample and sapphire plates thinly and uniformly. The temperature difference \( \Delta T \) between the sapphire (1) and (2) was measured with two thermocouples. A uniform external magnetic field \( H \) was applied along the \( x \) direction by using a superconducting solenoid magnet, where the maximum \( H \) value was 90 kOe. When \( H > 1 \) kOe (0.15 kOe), the magnetization of the YIG slab (YIG films) is well aligned along the \( H \) direction. We also confirmed that, in the range of \( -90 \) kOe < \( H \) < 90 kOe,
the magnetoresistance ratio of the chip heater is $< 0.03 \%$ in all the temperature range and the $H$ dependence of $\Delta T$ is negligibly small. Under this condition, we measured a DC electric voltage difference $V$ between the ends of the Pt layer of the Pt/YIG-slab and Pt/YIG-film samples. Hereafter, to quantitatively compare the temperature dependence of the voltage signals in different samples, we mainly plot the transverse thermopower $S \equiv (V/\Delta T)(L_x/L_y)$.

### III. RESULTS AND DISCUSSION

Now we start by presenting the experimental results of the LSSE in the Pt/YIG-slab sample. Figure 2(a) shows $S$ as a function of $H$ for various values of $T$, measured when $H$ was swept between $\pm 90$ kOe. When $\nabla T$ is applied to the sample, a clear $S$ signal appears due to the LSSE and its sign is reversed in response to the magnetization reversal of YIG. We found that, in the Pt/YIG-slab sample, the magnitude of the $S$ signal is suppressed by applying high magnetic fields at all the temperatures from 300 K to 5 K, while the magnitude of $M$ at each temperature is almost constant after the saturation [compare Figs. 2(a) and 2(b)]. This suppression cannot be explained by the normal Nernst effect in the Pt film since the $S$ signal in a Pt/GGG-slab sample, in which the YIG slab is replaced with a paramagnetic GGG slab, is much smaller than the $H$ dependence of the LSSE [see Fig. 2(a)]. We also confirmed that the critical suppression of the LSSE in the Pt/YIG-slab sample by high magnetic fields is irrelevant to the $H$ dependence of spin-current-related parameters, i.e. the spin Hall angle and spin-diffusion length, of Pt by measuring magnetoresistance in a similar Pt/YIG-slab system (see Appendix A).

In Fig. 3 we show the $T$ dependence of $S$ at the positive $H$ values and of the magnetic-field-induced suppression of $S$ in the Pt/YIG-slab sample. When the sample temperature is decreased from 300 K, the magnitude of $S$ monotonically increases and reaches its maximum value around $T = 75$ K [see Fig. 3(a)]. On decreasing the temperature further, the $S$ signal begins to decrease and goes to zero. This $T$ dependence of the LSSE with peak structure is qualitatively consistent with previous results [21, 31]. Importantly, as shown in Fig. 3(b), the suppression of the LSSE thermopower $\delta_{LSSE}$ also exhibits temperature dependence in the Pt/YIG-slab sample, where $\delta_{LSSE}$ is defined as $(S_{\text{max}} - S_{80\text{kOe}})/S_{\text{max}}$ with $S_{\text{max}}$ and $S_{80\text{kOe}}$ respectively being the $S$ values at the maximum point and at $H = 80$ kOe. We found that the suppression of the LSSE in the Pt/YIG-slab sample is almost constant ($20 \% < \delta_{LSSE} < 25 \%$) above 30 K and strongly enhanced below 30 K; the $\delta_{LSSE}$ value in the Pt/YIG-slab sample reaches $\sim 70 \%$ at $T = 5$ K [see Fig. 3(b)].

The critical field-induced suppression of the LSSE at low temperatures below 30 K is seemingly consistent with conventional SSE models combined with the effect of the Zeeman gap in magnon excitation. In the conventional formulation [44–46, 49], the LSSE voltage $V_{LSSE}$ is expressed as the following factor related to the magnon excitation:

$$V_{LSSE} \propto \int_{g_{\text{BE}}H}^{\infty} \frac{d \epsilon}{\epsilon} \mathcal{D}(\epsilon, H)[f_{\text{BE}}(\epsilon, T_m) - f_{\text{BE}}(\epsilon, T_c)]$$

$$\propto \int_{g_{\text{BE}}H}^{\infty} \frac{d \epsilon}{\epsilon} \mathcal{D}(\epsilon, H) \left. \frac{\partial f_{\text{BE}}}{\partial T_m} \right|_{T_m=T},$$

where $\mathcal{D}(\epsilon, H)$ is the density of states of magnons in the ferrimagnetic insulator. To obtain the differential form in Eq. 3, we assume that the modulation of the effective temperatures induced by the external temperature gradient is very small ($T_m \sim T_c$ and $|T_m(T_e) - T| \ll T$). We numerically calculated the right-hand side of Eq. 3.
FIG. 3: (a) Double logarithmic plot of the $T$ dependence of $S$ in the Pt/YIG-slab sample at $H = 1.8$ kOe (closed circles) and 80 kOe (open triangles). (b) $T$ dependence of the suppression $\delta_{\text{LSSE}}$ of the LSSE voltage by magnetic fields in the Pt/YIG-slab sample (circles). Here, $\delta_{\text{LSSE}} \equiv (S_{\text{max}} - S_{80\text{kOe}})/S_{\text{max}}$ with $S_{\text{max}}$ and $S_{80\text{kOe}}$ respectively being the $S$ values at the maximum point and at $H = 80$ kOe. A gray line shows the $T$ dependence of $\delta_{\text{LSSE}}$ calculated numerically from Eq. (3) based on the conventional formulation (see Appendix B).
dependence of the LSSE; we found that the magnitude of $S$ monotonically decreases with reducing $t_{\text{YIG}}$ in all the temperature range [Fig. 5(a)] and the dependence on $t_{\text{YIG}}$ of $S$ becomes stronger at lower temperatures [Fig. 5(f)]. These results demonstrate again the importance of low-frequency magnons with long characteristic lengths in the mechanism of the LSSE.

IV. CONCLUSION

In this study, we have investigated temperature and thickness dependences of high-magnetic-field response of the longitudinal spin Seebeck effect (LSSE) in Pt/Y$_3$Fe$_5$O$_{12}$ (YIG) junction systems. The experimental results show that the LSSE signal is suppressed by applying high magnetic fields at the temperatures ranging from 300 K to 5 K and this suppression is enhanced with decreasing the temperature in the Pt/YIG-slab system. The suppression of the LSSE appears even when the magnon gap induced by the Zeeman effect $g\mu_B H$ is much less than the thermal energy $k_B T$, suggesting that low-frequency magnons with energy comparable to or less than the Zeeman energy provide a dominant contribution to the LSSE rather than the higher-frequency magnons. This spectral non-uniformity of the thermo-spin conversion is associated with the characteristic lengths of the LSSE since the LSSE signal and its magnetic field dependence are strongly affected by the thickness of YIG. We anticipate that the comprehensive LSSE data reported here fill in the missing piece of the mechanism of the LSSE and lead to the development of theories of spin-current physics.

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APPENDIX A: SPIN-HALL MAGNETORESISTANCE IN PT/YIG-SLAB SYSTEM UNDER HIGH MAGNETIC FIELDS

To discuss the origin of the critical suppression of the LSSE by high magnetic fields, it is important to confirm that the observed behavior originates from the $H$ dependence of the magnon excitation in YIG, not from that of spin-current-related parameters of Pt. To do this, we measured the $H$ dependence of the spin-Hall magnetoresistance (SMR) in a similar Pt/YIG-slab system, in which the Pt layer is patterned into a Hall-bar shape [see Fig. 6(a)]. The SMR is a magnetoresistive effect that appears due to the combination action of the direct and inverse spin Hall effects in a paramagnetic metal coupled with magnetic moments in an attached ferromagnetic or ferrimagnetic material, which is well established in Pt/YIG junction systems. Since the SMR in the Pt/YIG system depends on the spin Hall angle and spin-diffusion length of Pt stronger than the LSSE, we can observe the $H$ dependence of these parameters via magnetoresistance measurements.

In Fig. 6(b), we show the magnetic-field-angle $\alpha$ dependence of the longitudinal resistivity $\rho$ of the Pt Hall bar on the YIG slab for various values of $H$, where $\alpha$ is defined as the angle between a charge current applied to the Pt Hall bar and an in-plane magnetic field [see Fig. 6(a)]. The $\rho$ values in the Pt-Hall-bar/YIG-slab sample vary with $\alpha$ in a sinusoidal manner with a period of 180°. This anisotropic resistivity change was confirmed to be due to the SMR. Notable is that the SMR signal in the Pt-Hall-bar/YIG-slab system is almost independent of the magnitude of the magnetic field not only at 300 K but also at 5 K where the large field-induced LSSE suppression was observed, when the magnetization of YIG is aligned along the $H$ direction ($H > 1$ kOe). This result indicates that the $H$ dependence of the spin-current-related parameters of Pt is too weak to affect the LSSE voltage at least below 90 kOe, showing that the observed suppression of the LSSE voltage under high magnetic fields is attributed to the YIG layer.

APPENDIX B: NUMERICAL CALCULATION OF EQUATION (3)

To clarify the $H$ dependence of the LSSE voltage $V_{LSSE}$ described by the conventional formulation, we numerically calculated the right-hand side of Eq. (3). For simplicity, we assume that magnons have a parabolic dispersion relation, where the density of states of magnons is affected by the Zeeman energy. As shown in Fig.
The importance of low-frequency magnons in the mechanism of a Hall-bar-shaped Pt film formed on a single-crystalline YIG slab sample used for measuring the SMR. The sample consists of a Hall-bar-shaped Pt film with a Pt Hall bar and a YIG slab, shown in Fig. 6(a). The magnon gap opening due to the Zeeman effect is much smaller than the thermal energy near room temperature even when the high magnetic field of 80 kOe is applied. Figure 6(b) shows the calculation results of the $H$ dependence of $V_{\text{LSSE}}$ for various values of $T$. We found that, although $V_{\text{LSSE}}$ described by Eq. (3) is suppressed by magnetic fields at low temperatures, the suppression around room temperature is much smaller than the observed $H$ dependence of the LSSE for the Pt/YIG-slab sample [compare Figs. 2 and 6(b)]. In Fig. 6(b), we plot the $T$ dependence of $\delta V_{\text{LSSE}}$ calculated from Eq. (3), which is defined as $(V_{\text{max}} - V_{\text{LSSE}})/V_{\text{max}}$ with $V_{\text{max}}$ and $V_{\text{LSSE}}$ respectively being the $V_{\text{LSSE}}$ values at the maximum point and at $H = 80$ kOe, indicating that the inconsistency between the experimental results and Eq. (3) increases with increasing $T$. As discussed above, the small suppression of $V_{\text{LSSE}}$ is attributed to the large energy difference between $g\mu_B H$ and $k_B T$, showing the importance of low-frequency magnons in the mechanism of the LSSE.

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[1] A. G. Gurevich and G. A. Melkov, *Magnetization Oscillations and Waves* (CRC, Boca Raton, FL, 1996).
[2] V. Cherepanov, I. Kolokolov, and V. L’vov, *The Saga of YIG: Spectra, Thermodynamics, Interaction and Relaxation of Magnons in a Complex Magnet*, Phys. Rep. 229, 81 (1993).
[3] G. P. Rodrigue, H. Meyer, and R. V. Jones, *Resonance Measurements in Magnetic Garnets*, J. Appl. Phys. 31, 3768 (1960).
[4] I. S. Tupitsyn, P. C. E. Stamp, and A. L. Burin, *Stability of Bose-Einstein Condensates of Hot Magnons in Yttrium Iron Garnet Films*, Phys. Rev. Lett. 100, 257202 (2008).
[5] G. E. W. Bauer, E. Saitoh, and B. J. van Wees, *Spin Caloritronics*, Nat. Mater. 11, 391 (2012).
[6] S. R. Boona, R. C. Myers, and J. P. Heremans, *Spin Caloritronics*, Energy Environ. Sci. 7, 885 (2014).
[7] S. Maekawa, H. Adachi, K. Uchida, J. Ieda, and E. Saitoh, *Spin Current: Experimental and Theoretical Aspects*, J. Phys. Soc. Jpn. 82, 102002 (2013).
[8] Y. Kajiwara, K. Harri, S. Takahashi, J. Ohe, K. Uchida, M. Mizuguchi, H. Umezawa, H. Kaiwai, K. Ando, K. Takahashi, S. Maekawa, and E. Saitoh, *Transmission of Electric Signals by Spin-Wave Interconversion in a Magnetic Insulator*, Nature 464, 262 (2010).
[9] Y. Tserkovnyak, A. Brataas, G. E. W. Bauer, and B. I. Halperin, *Nonlocal Magnetization Dynamics in Ferromagnetic Heterostructures*, Rev. Mod. Phys. 77, 1375 (2005).
[10] M. Weiler, M. Althammer, M. Schreier, J. Lotze, M. Perpeintner, S. Meyer, H. Huelb, R. Gross, A. Kamra, J. Xiao, Y.-T. Chen, H. Jiao, G. E. W. Bauer, and S. T. B. Goennenwein, *Experimental Test of the Spin Mixing Interface Conductivity Concept*, Phys. Rev. Lett. 111, 176601 (2013).
[11] Z. Qiu, K. Ando, K. Uchida, Y. Kajiwara, R. Takahashi, H. Nakayama, T. An, Y. Fujikawa, and E. Saitoh, *Spin Mixing Conductance at a Well-Controlled Platinum/Yttrium Iron Garnet Interface*, Appl. Phys. Lett. 103, 092404 (2013).
[12] A. Azevedo, L. H. Vilela-Leão, R. L. Rodríguez-Suárez, A. B. Oliveira, and S. M. Rezende, *de Effect in Ferromagnetic Resonance: Evidence of the Spin-Pumping Effect?*, J. Appl. Phys. 97, 10C715 (2005).
[13] E. Saitoh, M. Ueda, H. Miyajima, and G. Tatara, *Conversion of Spin Current into Charge Current at Room Temperature: Inverse Spin-Hall Effect*, Appl. Phys. Lett. 88, 182509 (2006).
[14] K. Uchida, S. Takahashi, K. Harri, J. Ieda, W. Koshibae, K. Ando, S. Maekawa, and E. Saitoh, *Observation of the Spin Seebeck Effect*, Nature 455, 776 (2008).
[15] K. Uchida, J. Xiao, H. Adachi, J. Ohe, S. Takahashi, J. Ieda, T. Ota, Y. Kajiwara, H. Umezawa, H. Kaiwai, G.
C. M. Jaworski, J. Yang, S. Mack, D. D. Awschalom, J. P. Heremans, and R. C. Myers, Observation of the Spin–Seebeck Effect in a Ferromagnetic Semiconductor, Nat. Mater. 9, 894 (2010).

K. Uchida, H. Adachi, T. Ota, H. Nakayama, S. Maekawa, and E. Saitoh, Long-Range Spin Seebeck Effect and Acoustic Spin Pumping, Nat. Mater. 10, 737 (2011).

D. Meier, T. Kuschel, F. D. Czeschka, H. Huebl, M. S. Wagner, M. Opel, I.-M. Imort, G. Reiss, A. Thomas, R. Gross, and S. T. B. Goennenwein, Local Charge and Spin Currents in Magnetothermal Landscapes, Phys. Rev. Lett. 108, 106602 (2012).

K. Uchida, T. Ota, H. Adachi, J. Xiao, T. Nonaka, Y. Kajiwara, G. E. W. Bauer, S. Maekawa, and E. Saitoh, Thermal Spin Pumping and Magnon-Phonon-Mediated Spin-Seebeck Effect, J. Appl. Phys. 111, 103903 (2012).

A. Kirihara, K. Uchida, Y. Kajiwara, M. Ishida, Y. Nakamura, T. Manako, E. Saitoh, and S. Yorozu, Spin-Current-Driven Thermoelectric Coating, Nat. Mater. 11, 686 (2012).

D. Qu, S. Y. Huang, J. Hu, R. Wu, and C. L. Chien, Intrinsic Spin Seebeck Effect in Au/YIG, Phys. Rev. Lett. 110, 067206 (2013).

T. Kikkawa, K. Uchida, Y. Shiomi, Z. Qiu, D. Hou, D. Tian, H. Nakayama, X.-F. Jin, and E. Saitoh, Longitudinal Spin Seebeck Effect Free from the Proximity Nernst Effect, Phys. Rev. Lett. 110, 067207 (2013).

K. Uchida, T. Kikkawa, Y. Shiomi, Z. Qiu, D. Hou, D. Tian, H. Nakayama, X.-F. Jin, and E. Saitoh, Longitudinal Spin Seebeck Effect Free from the Proximity Nernst Effect, Phys. Rev. Lett. 110, 067207 (2013).

T. Kikkawa, K. Uchida, Y. Shiomi, Z. Qiu, D. Hou, D. Tian, H. Nakayama, X.-F. Jin, and E. Saitoh, Longitudinal Spin Seebeck Effect Free from the Proximity Nernst Effect, Phys. Rev. Lett. 110, 067207 (2013).

K. Uchida, H. Adachi, T. Ota, H. Nakayama, S. Maekawa, and E. Saitoh, Long-Range Spin Seebeck Effect and Acoustic Spin Pumping, Nat. Mater. 10, 737 (2011).
[46] S. Hoffman, K. Sato, and Y. Tserkovnyak, Landau-Lifshitz Theory of the Longitudinal Spin Seebeck Effect, Phys. Rev. B 88, 064408 (2013).

[47] S. Y. Huang, X. Fan, D. Qu, Y. P. Chen, W. G. Wang, J. Wu, T. Y. Chen, J. Q. Xiao, and C. L. Chien, Transport Magnetic Proximity Effects in Platinum, Phys. Rev. Lett. 109, 107204 (2012).

[48] W. Nernst, Ueber die electromotorischen Kräfte, welche durch den Magnetismus in von einem Warmestrome durchflossenen Metallplatten geweckt werden, Ann. Phys. (Leipzig) 267, 760 (1887).

[49] S. A. Bender, R. A. Duine, and Y. Tserkovnyak, Electronic Pumping of Quasiequilibrium Bose-Einstein-Condensed Magnons, Phys. Rev. Lett. 108, 246601 (2012).

[50] J. S. Plant, ”Pseudo-Acoust’ Magnon Dispersion in Yttrium Iron Garnet, J. Phys. C 16, 7037 (1983).

[51] S. S.-L. Zhang and S. Zhang, Spin Convertance at Magnetic Interfaces, J. Phys. C 20, 1119 (1987).

[52] M. Agrawal, V. I. Vasyuchka, A. A. Serga, A. D. Karelowska, G. A. Melkov, and B. Hillebrands, Direct Measurement of Magnon Temperature: New Insight into Magnon-Phonon Coupling in Magnetic Insulators, Phys. Rev. Lett. 111, 107204 (2013).

[53] C. Kittel, Quantum Theory of Solids, 2nd revised printing (John Wiley and Sons, New York, 1987).

[54] M. A. Gilleo and S. Geller, Magnetic and Crystallographic Properties of Substituted Yttrium-Iron Garnet, 3Y2O3·xM2O3(5−x)Fe2O3, Phys. Rev. 110, 73 (1958).

[55] C. M. Srivastava and R. Aiyar, Spin Wave Stiffness Constants in Some Ferrimagnets, J. Phys. C 20, 1119 (1987).