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Observation of magnon-mediated current drag in Pt/yttrium iron garnet/Pt(Ta) trilayers

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Pure spin current, a flow of spin angular momentum without flow of any accompanying net charge, is generated in two common ways. One makes use of the spin Hall effect in normal metals (NM) with strong spin-orbit coupling, such as Pt or Ta. The other utilizes the collective motion of magnetic moments or spin waves with the quasi-particle excitations called magnons. A popular material for the latter is yttrium iron garnet, a magnetic insulator (MI). Here we demonstrate in NM/MI/NM trilayers that these two types of spin currents are interconvertible across the interfaces, predicated as the magnon-mediated current drag phenomenon. The transmitted signal scales linearly with the driving current without a threshold and follows the power-law T^n with n ranging from 1.5 to 2.5. Our results indicate that the NM/MI/NM trilayer structure can serve as a scalable pure spin current valve device which is an essential ingredient in spintronics.

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There has been intense research interest in pure spin current transport in both conducting and insulating materials. Whether by spin pumping^{1–4}, spin Seebeck effect (SSE)^{5–8} or spin Hall and inverse spin Hall effects^{9–15}, pure spin current generation and detection are typically accomplished in bilayers consisting of a magnetic and a non-magnetic layer^{2–4}. Either generation or detection, rarely both, is done by electrical means. Kajiwara *et al.*¹⁶ first demonstrated a lateral all-electrical device in which an electrical signal can transmit through yttrium iron garnet (YIG) over a macroscopic distance (~ 1 mm). The response (~ 1 nV) is highly nonlinear with a threshold in driving current, which was interpreted as the critical value for the spin transfer torque^{17,18} induced coherent precession of YIG magnetization. The effect also suggests that spin currents of two different types, that is, electronic^{9–15} and magnonic^{19–22}, are inter-convertible at the interfaces. However, the phenomenon has not been reproduced in a similar planar geometry.

Zhang *et al.*^{23,24} predicted a phenomenon with a different origin in sandwich structures, analogous to the conventional spin-valve device for spin-polarized charge currents^{25,26}. Rather than exciting a coherent precession of magnetization, at one interface, electrons in the NM create/annihilate magnons in the MI. The individual magnon creation/annihilation does not need to overcome any threshold; therefore, the interconversion takes place at any current. Due to the long magnon decay length in MI²⁷, this effect couples two remote electrical currents, which is called the magnon-mediated current drag. Moreover, the on and off states are controlled by the relative orientation between the polarization of the spin current and MI magnetization. In small lateral devices similar to that of Kajiwara, Cornelissen *et al.*²⁸ reported both ω - and 2ω nonlocal current responses in the a.c. measurements (ω is the frequency of a.c. current). The ω -response indicates a linear nonlocal current relation, which apparently does not share the same origin as that of the effect reported by Kajiwara. Nonlocal magnetoresistance was also reported in similar device geometry²⁹. However, it is unclear whether the reported effect indeed arises from the microscopic mechanism predicted by Zhang *et al.* An objective of this work is to experimentally establish the current drag effect in the sandwich geometry proposed by Zhang *et al.*

In this work, we first successfully fabricate Pt/YIG/Pt(Ta) trilayer structures using pulsed laser deposition in combination with sputtering and post-growth annealing. Below 220 K, the trilayers are sufficiently insulating and we observe nonlocal

responses when an in-plane magnetic field is swept or rotated. We find that the polarity of the nonlocal signal is opposite to each other between Pt/YIG/Pt and Pt/YIG/Ta, indicating the spin current origin of the effect. By investigating the effect at low temperatures, we show that the power-law dependence of the nonlocal signal is consistent with the prediction for the magnon-mediated current drag effect.

Results

Nonlocal device structure. Our NM/MI/NM trilayer device structure is schematically shown in Fig. 1a,b. The MI is a thin YIG film sandwiched by either two identical NM films or dissimilar NM films. Via the spin Hall effect, a charge current (J_{injected}) generates a pure spin current flowing in the z -direction with the spin polarization (σ) parallel to the y -direction. The conduction electrons in the bottom NM interact with the localized moments of the MI via the s - d exchange interaction at the interface, resulting in the creation or annihilation of magnons in the MI accompanied by spin-flips of conduction electrons in the bottom NM layer. Due to the nature of the s - d exchange interaction^{24,30}, that is, $H_{sd} = -J_{sd} \sum \sigma \cdot \mathbf{M}$, where J_{sd} is exchange coupling strength, when the magnetization of the MI (\mathbf{M}) is collinear with σ , magnons are created or annihilated depending on whether \mathbf{M} is parallel or anti-parallel to σ . As such, the interaction creates a non-equilibrium magnon population and spin accumulation in the MI which drives magnon diffusion. The excess/deficient magnons are then converted to a spin current in the top NM layer by the reverse process, which is converted to a charge current (J_{induced}) again in the top NM layer via the inverse spin Hall effect. When $\sigma \perp \mathbf{M}$, there is no non-equilibrium magnon population or spin accumulation and the spin current is absorbed by the MI. Consequently, there is no induced spin or charge current in the top NM layer (Fig. 1b). Remarkably, one can switch on and off the magnon creation/annihilation process by controlling the relative orientation between \mathbf{M} and σ . Conceptually, this structure functions as a valve for pure spin current.

Field-dependent nonlocal response in trilayer devices. Since both Pt and Ta have strong spin-orbit coupling with opposite signs in their spin Hall angle^{15,31,32}, we have fabricated three Pt (5 nm)/YIG (80 nm)/Pt (5 nm) devices and two Pt (5 nm)/YIG (80 nm)/Ta (5 nm) reference samples, which were deposited

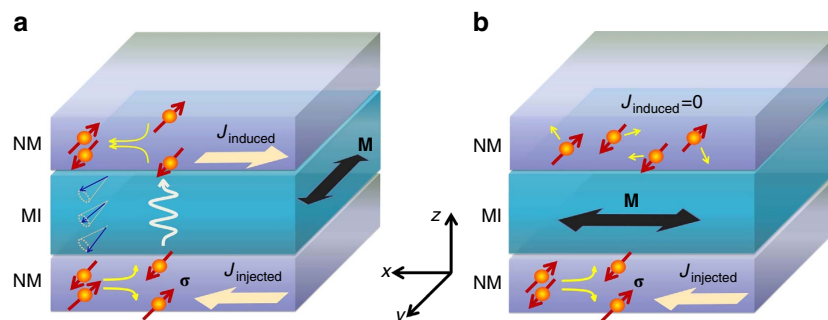


Figure 1 | Schematic illustration of spin current valve. (a) The transmission of spin current is switched on. Magnetization (\mathbf{M}) of magnetic insulator (MI) oriented collinearly with the spin polarization σ ($//y$) of the pure spin current in the bottom normal metal (NM) layer generated by the spin Hall effect with an electric current J_{injected} . The spin-flip scattering of conduction electrons at the bottom NM/MI interface can create ($\mathbf{M} \parallel -\sigma$) or annihilate ($\mathbf{M} \parallel \sigma$) magnons. A non-equilibrium magnon population extends to the top MI/NM interface, and the spin angular momentum carried by magnons is transferred to conduction electrons in the top NM layer. The pure spin current flowing perpendicular to the NM layer is then converted to a charge current (J_{induced}) via the inverse spin Hall effect. (b) The transmission of spin current is switched off. \mathbf{M} is perpendicular to the spin polarization σ of the spin current. In this geometry, the s - d exchange interaction between conduction electrons and local magnetic moments does not excite magnons in the MI. Consequently, there is no spin accumulation at the top MI/NM interface or induced charge current in the top NM layer.

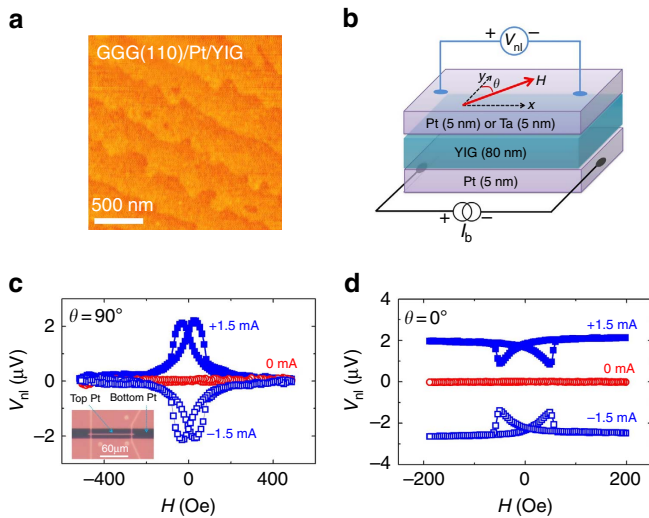


Figure 2 | Measurement geometry and field-dependent nonlocal signal.

(a) Atomic force microscopy image of 80 nm YIG film grown on 5 nm Pt. (b) Schematic illustration of the experimental set-up. I_b is the current applied to the bottom Pt layer, and V_{nl} is the nonlocal voltage measured at the top layer along the I_b direction. The applied in-plane magnetic field H makes an angle θ with the y -axis which is in plane and perpendicular to the current direction (x). (c) The field dependence of the nonlocal signal for H along I_b , that is, $\theta = 90^\circ$. The inset shows the optical image of GGG/Pt/YIG/Pt device. (d) The field-dependent nonlocal signal with H perpendicular to I_b , that is, $\theta = 0^\circ$. In both c and d, solid (empty) blue squares and empty red circles represent V_{nl} for +1.5 mA (−1.5 mA) and 0.0 mA bottom current, respectively.

on (110)-oriented $\text{Gd}_3\text{Ga}_5\text{O}_{12}$ (GGG) substrates (see Methods section for fabrication details). The inset of Fig. 2c shows an optic image for a GGG/Pt/YIG/Pt device. As illustrated in Fig. 2b, the bottom Pt layer is used to inject current I_b , while the top layer, either Pt or Ta, functions as a detector to measure the induced current or the nonlocal voltage V_{nl} . An in-plane H is either swept in a fixed direction or rotated with a continuously varying angle of θ measured from the y -direction. We find that the high-quality YIG/Pt interface is essential to the observation of the spin current transmission. As shown in Fig. 2a, the morphology of a YIG film tracks the atomically flat terraces of the GGG (110) surface³³ in spite of a layer of Pt in between. The excellent interface quality is verified by both the SSE⁵ (see Supplementary Note 5 and Supplementary Fig. 6) and the spin Hall magnetoresistance (SMR)^{34,35} (see Supplementary Note 3 and Supplementary Fig. 3) in the same devices. The 80-nm-thick YIG films are nearly insulating but have small leakage at high temperatures. However, the resistance between the top and bottom NM layers increases exponentially as the temperature (T) decreases (see Supplementary Note 2 and Supplementary Fig. 2), and exceeds 20 GΩ at and below 220 K. Therefore, all the nonlocal measurements were performed below 220 K to avoid any parasitic signal from the small leakage current. In V_{nl} , we remove a non-zero background signal that exists even at $I_b = 0$.

Figure 2c,d plot the field dependence of V_{nl} at 220 K. When H is swept along I_b , that is, $\theta = 90^\circ$ (Fig. 2c), V_{nl} is a constant at $I_b = 0$ (red). However, at $I_b = +1.5$ mA, V_{nl} shows a clear hysteresis with two positive peaks tracking the coercive fields of the YIG film, indicating that V_{nl} is closely related to the magnetization state of YIG. As the I_b is reversed, V_{nl} also reverses the sign. In principle, a sign reversal can occur if there is a finite leakage current flowing in the top layer. Through the magnetoresistance, this current can produce a hysteretic voltage signal. Estimating from the leakage current, we find that the

relative change in V_{nl} due to this effect is at least three orders of magnitude smaller than the observed nonlocal voltage signal (see Supplementary Note 4 and Supplementary Figs 4 and 5). Therefore, we exclude the leakage current as the source of the nonlocal signal. Note that $V_{nl}(\pm 1.5$ mA) is the same as $V_{nl}(0$ mA) at the saturation state ($H > 200$ Oe) when $\sigma \perp \mathbf{M}$, suggesting that magnon creation/annihilation is totally suppressed. For the field sweeps with $\theta = 0^\circ$ (Fig. 2d), σ is collinear with \mathbf{M} at high fields, interface magnon creation/annihilation results in a full current drag signal. Clearly, $V_{nl}(+1.5$ mA) is different from $V_{nl}(0$ mA) at the saturation fields and reverses the sign when I_b reverses. It is interesting to note that $V_{nl}(\pm 1.5$ mA) differ from $V_{nl}(0$ mA) at the coercive fields. One would expect them to be the same since the average magnetization should point to the x -direction at the coercive fields, which would correspond to the saturation states for $\theta = 90^\circ$ in Fig. 2c. This discrepancy can be explained by the multi-domain state of YIG in which the actual \mathbf{M} is distributed over a range of angles around $\theta = 90^\circ$, and the collinear component of \mathbf{M} turns on the magnon channel and yields a nonzero V_{nl} . To investigate the phenomenon in the single-domain state, we perform the following experiments.

Angle-dependent nonlocal response of single-domain YIG.

Figure 3a presents V_{nl} in GGG/Pt/YIG/Pt as a function of θ between \mathbf{M} and σ at 220 K, as illustrated in Fig. 2b. The 80 nm (110)-oriented YIG grown on Pt has a well-defined uniaxial anisotropy with an anisotropy field < 200 Oe. The applied magnetic field (1,000 Oe) is sufficiently strong not only to set YIG into a single-domain state, but also to rotate \mathbf{M} with it. For all positive I_b (solid symbols), V_{nl} exhibits maxima at $\theta = 0^\circ$ and 180° (\mathbf{M} collinear with σ), but minima at $\theta = 90^\circ$ and 270° ($\mathbf{M} \perp \sigma$). V_{nl} changes the sign as I_b is reversed (empty symbols). At $\theta = 90^\circ$ and 270° , the nonlocal signal for $\pm I_b$ coincides with $V_{nl}(0$ mA), further validating that the spin current is in the off state when $\mathbf{M} \perp \sigma$. Similar angular dependent measurements are also taken on a GGG/Pt/YIG/Ta device and the results are depicted in Fig. 3d. For the same measurement geometry and the same polarity of I_b , we find that V_{nl} of GGG/Pt/YIG/Ta has the opposite sign to that of GGG/Pt/YIG/Pt, which is just expected from the opposite signs in their spin Hall angle. The V_{nl} sign difference here is another piece of critical evidence for the magnon-mediated mechanism, as opposed to other extrinsic ones such as leakage.

An interesting feature to note here is that V_{nl} at $\theta = 0^\circ$ and 180° shows a slight but reproducible difference that is independent of the current polarity but increases with the increasing magnitude of I_b . We attribute this phenomenon to the SSE contribution since the joule heating in the bottom Pt layer unavoidably generates a small vertical temperature gradient, which in turn launches an upward spin current in YIG entering the top Pt (or Ta) layer. As \mathbf{M} reverses, so does the spin polarization, which consequently produces two different SSE signal levels between $\theta = 0^\circ$ and 180° . Combining these two effects, we can fit the angular dependence data using:

$$V_{nl} = V_0 + V_{\text{SSE}} \cos\theta + V_{\text{Drag}} \cos^2\theta \quad (1)$$

where V_0 is an offset voltage insensitive to the magnetization orientation, V_{SSE} is the SSE voltage amplitude and V_{Drag} represents the amplitude of the current drag signal. The solid red curves in Fig. 3a,d fit the experimental data remarkably well, and the extracted fitting results are plotted in Fig. 3b,e for GGG/Pt/YIG/Pt and GGG/Pt/YIG/Ta devices, respectively. Two conclusions can be evidently drawn from these results. First, the magnitude of the current drag signal (red circles) scales linearly

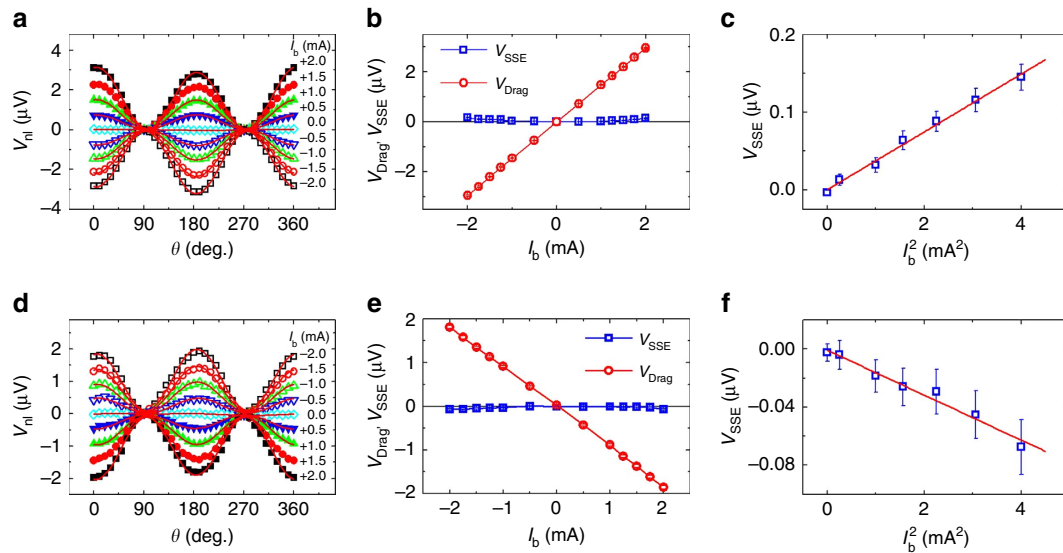


Figure 3 | Angular and current dependence of nonlocal signal. (a,d) Angular dependence of nonlocal signal at different currents in the bottom Pt layer for GGG/Pt/YIG/Pt and GGG/Pt/YIG/Ta, respectively. The magnetic field is fixed at 1,000 Oe and rotated in plane. In **a** and **d**, solid symbols indicate positive I_b , and empty symbols indicate negative I_b . Red curves are least squares fits using equation (1). (b,e) Show the I_b dependence of the current drag signal (V_{Drag}) and the spin Seebeck signal (V_{SSE}) for GGG/Pt/YIG/Pt and GGG/Pt/YIG/Ta, respectively. (c,f) The spin Seebeck signal as a function of I_b^2 for GGG/Pt/YIG/Pt and GGG/Pt/YIG/Ta, respectively, the red curves are the linear fits. The error bars are from fitting using equation (1) in **a** and **d**.

with the driving current, that is, $V_{\text{Drag}} \propto I_b$. This is in stark contrast with the highly nonlinear behaviour¹⁶. Second, the weak current dependence of the SSE contribution follows $V_{\text{SSE}} \sim I_b^2$ (as shown in Fig. 3c,f), which is characteristic of thermoelectric effects. Compared with usual bilayers, trilayer structures may have an enhanced SSE contribution due to the presence of the second heavy metal layer that draws an extra heat-driven spin current. Carefully designed experiments are needed to separate this effect.

Temperature dependence of nonlocal responses. According to Zhang, *et al.*²⁴, the temperature dependence of the injection interface spin convertance $G_{\text{em}} = \left(\frac{T}{T_c}\right)^{3/2}$, where T_c is the Curie temperature of the MI; for the detection interface, the spin convertance G_{me} is proportional to $\frac{T}{T_F}$, where T_F is the Fermi temperature of the NM layer. In the most simplified picture which is strictly applicable only for very thick films, the current drag signal should be proportional to the product of the two spin current convertances, that is, $V_{\text{Drag}} \propto G_{\text{em}} \cdot G_{\text{me}} \propto T^{5/2}$. The representative angular dependence measurements below 220 K are shown in Fig. 4a,c for GGG/Pt/YIG/Pt and GGG/Pt/YIG/Ta devices, respectively. For both the samples, I_b is set at +2 mA and H is held at 1,000 Oe. The magnitude of the current drag signal decreases progressively with decreasing temperature for both the devices. By fitting V_{nl} using equation (1), we extract the magnitude of V_{Drag} and V_{SSE} shown in Fig. 4b,d. Apart from the expected sign difference, the magnitude of V_{Drag} in both the devices monotonically decreases with decreasing temperature. In fact, both data sets can be well fitted by a power-law $V_{\text{Drag}} = V_{\text{Drag}}^0 T^n$ (red solid curves in Fig. 4b,d), where V_{Drag}^0 is a pre-factor. The extracted exponent n is 2.21 for GGG/Pt/YIG/Pt and 1.88 for GGG/Pt/YIG/Ta, falling in the range between 1.5 and 2.5. It should be pointed out that the full picture described in ref. 24 actually contains other quantities that have weak temperature dependence. The deviation of the exponent from 2.5 is fully expected if these factors are considered. On the other hand, the V_{SSE} is found to be relatively insensitive to temperature, suggesting a completely different mechanism.

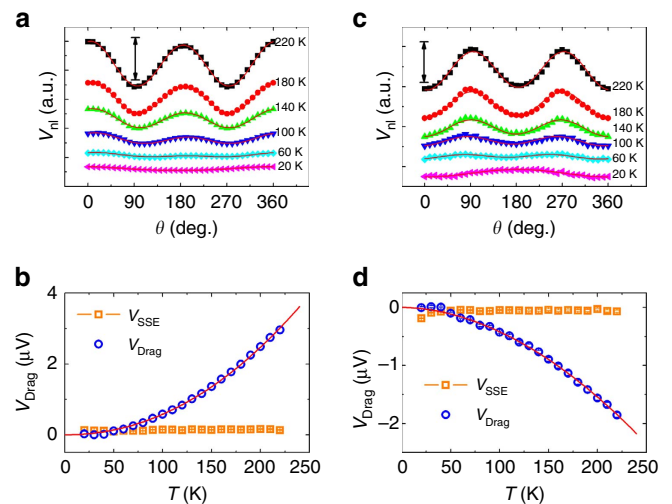


Figure 4 | Temperature dependence of nonlocal signal. (a,c) Angular dependence of the nonlocal signal at different temperatures for GGG/Pt/YIG/Pt and GGG/Pt/YIG/Ta, respectively. During the measurements, I_b was fixed at +2 mA. The curves are vertically shifted for clarity, the black arrows in **a** and **c** represent the magnitude scale of 2.80 and 1.98 μV , respectively. Red solid curves in **a** and **c** are the fits using equation (1). (b,d) The temperature dependence of the extracted current drag signal (V_{Drag}) and spin Seebeck signal (V_{SSE}) for GGG/Pt/YIG/Pt and GGG/Pt/YIG/Ta, respectively. Red solid curves in **b** and **d** are the fits using $V_{\text{Drag}} = V_{\text{Drag}}^0 T^n$, here, $n = 2.21$ for the GGG/Pt/YIG/Pt device, and $n = 1.88$ for the GGG/Pt/YIG/Ta device.

In conclusion, we experimentally establish the magnon-mediated current drag effect in NM/MI/NM trilayer structures by investigating the field, angle, current and temperature dependences of the nonlocal signal. The spin information carried by conduction electrons and magnons in different materials can be interconverted at the interfaces. Such structures can serve as

pure spin current valve devices since rotating the in-plane magnetization of the MI by 90° provides a digital on–off switch of the spin current. Furthermore, such structures also provide analogue functionality since rotating the in-plane magnetization of the MI provides analogue sinusoidal modulation of the spin current. Due to the extremely low damping in the MI, transmission of the pure spin currents can occur over relatively long distances providing the functionality of a pure spin interconnect.

Methods

Fabrication. A Hall bar was first defined in the photo-resist layer on a (110)-oriented single crystalline GGG substrate using photolithography with the channel width of $20\ \mu\text{m}$ and the length of $300\ \mu\text{m}$ between two voltage electrodes. Then the bottom Pt layer was deposited on the open Hall bar area by d.c. magnetron sputtering. During sputtering, argon pressure was $5\ \text{mTorr}$, substrate temperature was kept at $300\ \text{K}$, and the d.c. sputtering power was $37.5\ \text{W}$. The deposition rate of Pt was $0.77\ \text{\AA s}^{-1}$ and the Pt layer thickness was $5\ \text{nm}$. After liftoff, an 80-nm -thick YIG film was deposited at 450°C with O_2 pressure of $1.5\ \text{mTorr}$ by pulsed laser deposition to cover the surface of the entire sample. The as-grown YIG film became crystallized and magnetized after rapid thermal annealing between 800 and 850°C for $200\ \text{s}$. We had explored a range of growth temperatures, different annealing conditions, different pulsed laser deposition rates and YIG film thicknesses and had experienced many difficulties such as YIG film cracking, peeling off for thicker YIG films, conducting, non-magnetic and so on before we identified the working window. The magnetic properties of YIG were investigated by vibrating sample magnetometer (see Supplementary Note 1 and Supplementary Fig. 1). The surface morphology of YIG was monitored by atomic force microscopy. Clear atomic terraces were observed and the root-mean-square roughness on terraces was $\sim 0.14\ \text{nm}$, indicating a very flat YIG surface. The top Pt and Ta patterns were defined using standard e-beam lithography, followed by magnetron sputtering deposition and lift-off procedures. Before Pt (or Ta) deposition, $60\ \text{s}$ argon ion milling was used to remove any polymer residues from the YIG surface. The deposition conditions for top Pt and Ta were the same as those for bottom Pt. The top Pt and Ta strips are $2\ \mu\text{m}$ in width, and 70 and $60\ \mu\text{m}$ in length, respectively. To generate a vertical temperature gradient in separate longitudinal Spin Seebeck effect measurements, which we conducted after the nonlocal measurements were finished, we deposited 300-nm -thick Al_2O_3 on top and then Cr ($5\ \text{nm}$)/Au ($50\ \text{nm}$), which serves as a heater for SSE measurements.

Transport measurement. For all transport measurements, the current was fed to the devices using a Keithley 2,400 d.c. current source, and the voltage was measured by a Keithley 2182A nano-voltmeter. The field dependence measurements were carried out using a closed-cycle system, while the angular dependent measurements were performed by a physical property measurement system equipped with a rotatory sample holder. For the nonlocal measurements, the excitation current in the bottom Pt is usually no more than $2\ \text{mA}$; for the local magnetoresistance measurements, the current applied in top Pt and Ta was $1\ \mu\text{A}$, while the current used in bottom Pt is $10\ \mu\text{A}$. For the SSE measurements, the heating current applied in the top Au layer is $30\ \text{mA}$. In all the measurements, extra precaution was taken to ensure the correct polarity of both current and voltage.

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Author contributions

J.S. designed and supervised the project. J.L. and Y.X. performed the device fabrication and transport measurements with the help of Z.L. M.A. performed the pulsed laser deposition of the sandwich structures and characterization with the help of C.T. S.Z. and R.L. contributed to data analyses. J.L. and J.S. wrote the manuscript and all the authors contributed to the final version of manuscript.

Additional information

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