

Observation of the Magnon Hall Magnetoresistance Effect

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Interconversion between charge and spin currents via spin-orbit coupling underpins spin orbitronics. Magnons, which are the quanta of spin waves, can exchange angular momentum with conduction-electron spins through spin-flip scattering, suggesting a direct route for charge-to-magnon conversion. Here, we predict that in single-layer ferromagnets, an applied electric current induces a transverse magnon current, producing electrical magnon Hall and inverse magnon Hall effects that share the symmetry of the spin Hall and inverse spin Hall effects. This effect gives rise to a magnon Hall magnetoresistance in CoFeB and NiFe, with an efficiency comparable to the spin Hall effect and a characteristic decay length on the order of micrometers, far exceeding typical electron spin diffusion lengths. By enabling the direct generation and detection of long-range magnon currents, our findings open new pathways for low-loss, on-chip spin-based logic and energy-harvesting devices.

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The electrical spin Hall effect has fueled the rapid development of spintronics and its applications in information storage and transfer [1,2]. As depicted in Fig. 1(a), the spin Hall effect in a nonmagnetic material converts an electric current into a transversely propagating spin current, which is a flow of spin angular momentum via spin-orbit coupling [3]. The spin-orbit coupling also exists in ferromagnetic metals, which leads to the well-known anomalous Hall effect and the spin anomalous Hall effect, as shown in Fig. 1(b), along with other unconventional magnetization-dependent spin Hall effects [4–7]. In a ferromagnet, there exists another spin angular momentum carrier, magnons, which are the quantization of spin waves. Magnons can exchange spin angular momentum with electrons, as has been demonstrated at an interface between a nonmagnetic metal and a magnetic insulator [8] mediated by the spin-flip scattering at the interface [9]. Reciprocally, the spin-flip scattering also transfers spin angular momentum from magnon current to electron spin current, as has been demonstrated in the spin Seebeck effect detection [10].

In a ferromagnetic metal, an applied charge current generates a transverse spin current through spin-orbit coupling, such as the spin Hall or spin anomalous Hall effects. This transverse spin current then undergoes spin-flip scattering with the local magnetic moments. Microscopically, each spin-flip event transfers angular momentum from itinerant electrons to magnons, which results in a dragged transverse magnon current. As illustrated in Fig. 1(c), we refer to the electrical generation of transverse magnon current as the electrical magnon Hall effect, a response permitted by symmetry in a ferromagnetic metal. The electrical magnon Hall effect is mathematically expressed as

$$\vec{Q}_m = \theta_m \frac{\hbar}{e} \vec{J}_e \times \hat{m}, \quad (1)$$

where $\vec{Q}_m$ is the magnon spin current, $\hbar$ is the reduced Planck constant, e is the electron charge, $\vec{J}_e$ is the applied electric current, and $\hat{m}$ is the unit magnetization vector, and θ_m describes the efficiency of the electrical magnon Hall effect, which depends on both the strength of the spin-orbit coupling and spin-flip scattering in the FM.

Similarly, the Onsager principle suggests that the flow of magnon current can also generate a transversely flowing electric current, analogous to the inverse spin Hall effect, which can be described as $\vec{J}_e = \theta_m (e/\hbar) \vec{Q}_m \times \hat{m}$. It is important to clarify that the *electrical* magnon Hall effect describes the interconversion between the charge current and transverse magnon spin current. This mechanism is

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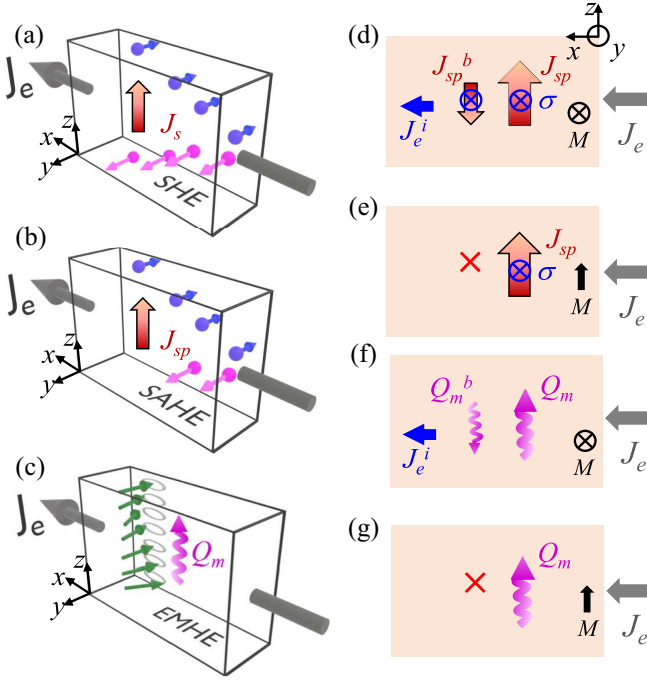


FIG. 1. (a) Schematics of the conventional spin Hall effect in a nonmagnetic material (NM), where J_e is the applied electric current and J_s is the generated spin current. (b),(c) In a ferromagnetic material (FM), an electric current can generate (b) a spin-polarized current J_{sp} via the spin anomalous Hall effect and (c) a magnon current Q_m via the electrical magnon Hall effect. (d),(e) Side-view illustration of the anomalous Hall magnetoresistance. In the configuration of (d), out-of-plane spin-polarized current J_{sp} generates a backflow J_{sp}^b , which then generates a secondary electric current J_e^i via the inverse effect. In the configuration of (e), no out-of-plane J_{sp} is generated, resulting in the absence of J_e^i . (f),(g) Side-view illustration of the magnon Hall magnetoresistance. In the configuration of (f), out-of-plane flowing magnon current Q_m generates a backflow Q_m^b , which then generates J_e^i via the inverse effect. This process is not allowed in configuration of (g).

fundamentally distinct from the magnon Hall effect, often referred to as the thermal Hall effect, where thermally driven magnons are deflected transversely due to the Dzyaloshinskii-Moriya interactions [11].

Although the existence of the electrical magnon Hall effect and its inverse effect is allowed by symmetry, their experimental demonstration has so far been elusive. Here, by measuring the magnon Hall magnetoresistance, we reveal the significant electrical magnon Hall effect as well as the long decaying length in single-layer ferromagnetic metals.

The magnon Hall magnetoresistance is illustrated in Figs. 1(f) and 1(g). When an electric field is applied in the x direction, and magnetization is in the y -direction, as shown in Fig. 1(f), the electrical magnon Hall effect generates a magnon current Q_m flowing in the z -direction. In a thin film geometry, where the thickness is limited in the z -direction,

magnon accumulation at the surface induces a backflow of magnon current Q_m^b . The backflow magnon current further generates a secondary electric current J_e^i via the inverse electrical magnon Hall effect. Such a process does not exist when magnetization is aligned in the z -direction, as shown in Fig. 1(g). Instead, according to Eq. (1), a magnon current is generated that flows in the y -direction. In a thin film geometry with extended lateral dimension, the influence of the backflow magnon current in the y -direction is much weaker than that in the z -direction. Therefore, a difference in the magnetoresistance is expected between the two configurations in Figs. 1(f) and 1(g), which we refer to as the magnon Hall magnetoresistance.

The magnon Hall magnetoresistance has the exact symmetry as the anomalous Hall magnetoresistance in ferromagnetic metals [12], as shown in Figs. 1(d) and 1(e) except the latter is due to the spin anomalous Hall effect. The two effects can be distinguished via the different characteristic lengths. The anomalous Hall magnetoresistance is more pronounced when the ferromagnet thickness is comparable to the spin diffusion length, typically on the order of a few nanometers (See Supplemental Material [13] and Ref. [22]). When the ferromagnet thickness significantly exceeds the spin diffusion length, on the order of several hundred nanometers, the effect of the anomalous Hall magnetoresistance is suppressed. In contrast, the magnon Hall magnetoresistance, governed by the magnon diffusion lengths, becomes prominent. Remarkably, prior to our discovery, the magnetization-dependent resistance in thick ferromagnetic metals has been largely overlooked.

We study two magnetic materials: $\text{Co}_{60}\text{Fe}_{20}\text{B}_{20}$ (CoFeB) and $\text{Ni}_{80}\text{Fe}_{20}$ (Permalloy, Py), since both have relatively long magnon diffusion lengths due to small magnetic damping [23,24]. We prepare thin films of CoFeB and Py through magnetron sputtering onto Si substrates with a thermally oxidized SiO_2 surface or glass substrates. For Py films thicker than 2000 nm, we perform the deposition in multiple steps, with a 30-min pause after every 2000 nm of Py deposition, in order to prevent possible cracking and excessive stress accumulation. We pattern films into Hall-bar shapes with 5 mm and 100 μm of length and width, respectively, for electrical transport measurements. Each sample is protected by a 5 nm-MgO or 2 nm- Al_2O_3 layer from oxidation.

The electrical resistance is measured by the standard four-probe technique via the patterned Hall bar with a charge current $I = 0.1$ mA applied in the x -direction, and the voltage is measured along the same direction. The sample is mounted on a rotational stage under a 1.8 T external magnetic field. This field is large enough to saturate magnetization in the x -, y -, and z -directions for both CoFeB and Py. The rotational stage enables a 2° angle step of magnetic field rotation in the xy -, yz -, and xz -planes, which are referred to as the α -, β -, and γ -scans, respectively, as shown in Figs. 2(a)–2(c). The α , β , and γ are the angles between the magnetic field and

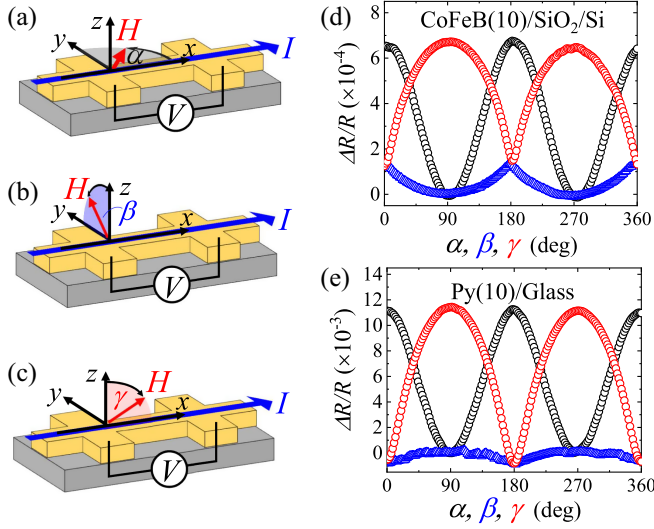


FIG. 2. Schematic illustration of the magnetoresistance measurement. A charge current $I = 0.1$ mA is applied along the x -direction all three cases, with a 1.8 T external magnetic field rotates in the (a) xy -, (b) yz -, and (c) xz -planes, which are referred to as the α -, β -, and γ -scans, respectively. The magnetic-field-angular-dependent magnetoresistance obtained for (d) CoFeB(10)/SiO₂/Si and (e) Py(10)/Glass. Number in parentheses represents thickness.

the x -, z -, and z -axis, respectively, in the α , β , and γ scans, whose magnetoresistance ratios are defined as $[R(\alpha, \beta \text{ or } \gamma = 0^\circ) - R(\alpha, \beta \text{ or } \gamma = 90^\circ)]/R(\alpha, \beta \text{ or } \gamma = 0^\circ)$.

For ferromagnetic metals, the magnetoresistance is generally the highest when the magnetization (M) is parallel to the applied current (I) due to the conventional anisotropic magnetoresistance [25,26]. Therefore, in the 10-nm-thick CoFeB and Py thin films, we observe a W-shaped α -scan (black curves) and a M-shaped γ -scan (red curves), as shown in Figs. 2(d) and 2(e). In the β -scans, where the magnetization rotates in the plane normal to the applied current, no magnetoresistance ratio is expected if the thickness is comparable to the width of the stripe, governed by symmetry. But when the film thickness is much less than the width and magnon (or spin) diffusion length, due to the backflow of magnon (or spin) current in the thickness direction, a positive magnetoresistance ratio in the β -scans is expected, revealing the magnon (or spin) current contributions.

Two distinctive behaviors of the β -scans (blue curves) are shown in Figs. 2(d) and 2(e). We observe a W-shape with $R(\hat{m} \parallel \hat{z}) > R(\hat{m} \parallel \hat{y})$ for CoFeB and an M-shape with $R(\hat{m} \parallel \hat{z}) < R(\hat{m} \parallel \hat{y})$ for Py. Besides the aforementioned spin Hall and magnon Hall contributions, the magnetoresistance in the β -scans is also influenced by the geometric anisotropic magnetoresistance (geometric MR) [25,27,28].

The geometric MR has been understood within the framework of the Boltzmann method. Generally speaking, anisotropic magnetoresistance arises from the different scattering rates between electron wavevectors parallel to

and perpendicular to local magnetizations [25]. In a thin film, surface scattering causes additional differences in the distributions of electron wave vectors with and without out-of-plane components. The geometric MR generally gives rise to a higher resistance when magnetization is in the plane in the y -direction than that with magnetization out of plane in the z -direction. Therefore, the geometric MR presents an M-shape in the β -scans (see Supplemental Material [13] for detailed derivation).

On the other hand, the anomalous Hall and magnon Hall magnetoresistance caused by electron and magnon spin currents, respectively, similar to those observed in the spin Hall magnetoresistance in YIG/Pt bilayer [29], lead to the opposite MR behaviors compared to the geometric MR, i.e., the resistance is higher when magnetization is in the z -direction than that with y -direction magnetization. Hence, the spin Hall magnetoresistance and magnon Hall magnetoresistance give rise to a W-shape in the β -scan measurement.

The β -scan magnetoresistance observed in Fig. 2 is due to the competition of the two opposite behaviors. In Py, the anisotropic magnetoresistance (extrapolated from the α -scan) is as large as 1.1%. In these films, the β -scans exhibit a M-shape, suggesting the dominance of geometric MR. However, in CoFeB, the anisotropic magnetoresistance is extrapolated to be only 0.06%, which is more than 1 order smaller than that in Py. Therefore, the geometric MR, which scales with the anisotropic magnetoresistance, is significantly suppressed. Leading to the W-shaped β -scan magnetoresistance curve. Therefore, CoFeB is an ideal candidate for investigating the magnon Hall magnetoresistance via thickness-dependent study without significant complications from the geometric MR.

In a single-layer ferromagnetic thin film, the thickness-dependent β -scan magnetoresistance is expressed as

$$\begin{aligned} MR^{\beta\text{-scan}} &= \frac{R_z - R_y}{R_z} \\ &= \frac{2\theta_{\text{SH}}^2}{t} \lambda_{\text{sf}} \tanh \frac{t}{2\lambda_{\text{sf}}} \\ &\quad + \frac{2\theta_m^2}{t} \lambda_m \tanh \frac{t}{2\lambda_m} + G(a, \lambda, t), \end{aligned} \quad (2)$$

where the three MR terms successively represent the contributions from anomalous Hall magnetoresistance, magnon Hall magnetoresistance, and geometric MR. In this equation, t is film thickness, θ_{SH} is effective spin Hall angle, λ_{sf} is spin diffusion length, θ_m is effective charge-to-magnon conversion efficiency, λ_m is magnon diffusion length, and $G(a, \lambda, t)$ is a function of bulk anisotropic magnetoresistance (a), the electron mean free path (λ), and film thickness (t).

In Eq. (2), the hyperbolic tangent in the first term saturates to a finite value when the film thickness t is much greater than λ_{sf} . $G(a, \lambda, t)$ is a geometric function that decays to zero when the film thickness is much greater than

the mean free path, $t \gg \lambda$ (see part 6 of Supplemental Material [13]). In separate measurements, we obtain the spin diffusion length and electronic mean free path for CoFeB as 1.7 nm and 2.4 nm, respectively (see part 6 in [13]); both the anomalous Hall and geometric MR are expected to decay significantly once the CoFeB thickness is above 20 nm. On the other hand, since the magnon diffusion length can be longer than 100 nm, we expect the magnon Hall magnetoresistance to dominate in thick CoFeB films during the β -scans magnetoresistance measurement.

The thickness dependence of β -scan magnetoresistance in CoFeB film is shown in Fig. 3(a). W-shaped curves are unambiguously observed for all CoFeB film thicknesses up to 1000 nm. As shown in Fig. 3(b), the β -scan magnetoresistance ratio initially decreases sharply until about 10 nm, followed by a much slower decay as CoFeB thickness increases. The initial decay is attributed to the quick saturation of anomalous Hall magnetoresistance and geometric MR. The impact of these effects on the entire film roughly scales with $1/t$, after the film thickness t is greater than the relevant characteristic length. However, the magnon spin current, which has a long diffusion length, keeps increasing as t increases. Therefore, the magnon Hall magnetoresistance results in a much slower decay in the β -scan magnetoresistance for thick CoFeB.

To characterize the magnon diffusion length λ_m , we fit the β -scan magnetoresistance ratio after subtracting the obtained geometric MR contribution vs CoFeB thickness

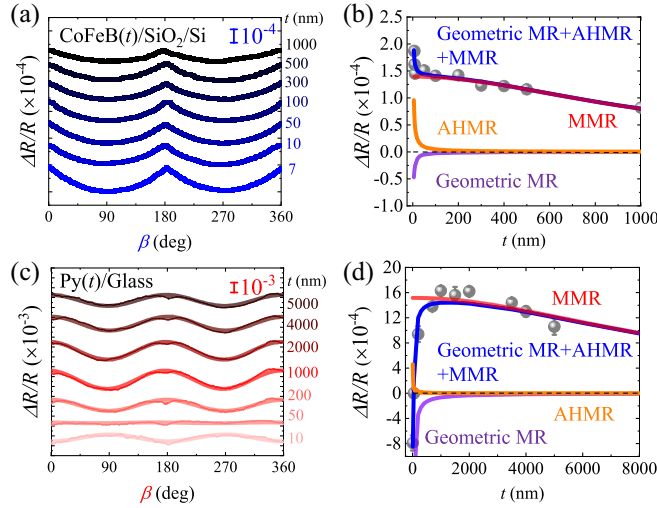


FIG. 3. (a) CoFeB β -scan MR result from 7 to 1000 nm and (c) Py β -scan MR result from 10 to 5000 nm. Curves are shifted for comparison. The (b) CoFeB and (d) Py thickness dependent β -scan MR. The gray dots are the experimental data. The purple lines are the estimated geometric MR obtained from the Boltzman method. The orange and the red lines are, respectively, the fitted anomalous Hall and magnon Hall magnetoresistance using Eq. (2). The blue solid lines are the sum of geometric MR, anomalous Hall magnetoresistance, and magnon Hall magnetoresistance, which nicely follow the experimental data.

[Fig. 3(b)] using Eq. (2) (see Supplemental Material [13]). From the fitting, we obtain the magnon spin Hall angle $\theta_m = 1.2\%$, and the CoFeB magnon diffusion length $\lambda_m = 310 \pm 53$ nm, which is 2 orders of magnitude longer than the λ_{sf} for conduction electrons.

To further demonstrate that the transverse magnon generation is universal for ferromagnetic metals, we also study the thickness-dependent β -scan magnetoresistance in Py. As shown in Figs. 3(c) and 3(d), the β -scan magnetoresistance in Py exhibits an M-shaped curve at 10 nm. This suggests that the geometric MR is significant in Py, likely due to the large bulk anisotropic magnetoresistance. Nevertheless, β -scan magnetoresistance decreases to near zero in 50 nm thick Py and is flipped to the W-shaped curve when Py thickness is larger than 200 nm. After peaking at 1000 nm, the MR ratio slowly decays and maintains positive even at 5000 nm. These results reveal the long λ_m in Py. By fitting the magnetoresistance ratio after subtracting the geometric MR contribution in Py [Fig. 3(d)] using Eq. (2), we obtain a charge-to-magnon conversion efficiency $\theta_m = 3.9\%$ for Py, comparable to the spin Hall angle of Py [30]. The magnon diffusion length λ_m is estimated as 2857 ± 357 nm, which is consistent with the reported coherent spin-wave decay length range (1.4 – 2.1 μm) for Py [31,32].

Our consistent results of the magnon Hall magnetoresistance in CoFeB and Py suggest that the interconversion between electric current and magnon current is universal in ferromagnetic metals. This long-overlooked effect may transform the circuit design for spin-based logic circuits, since the magnon diffusion length is orders higher than the electron spin diffusion length. Moreover, in applications such as the spin pumping and spin Seebeck effect, the multiplication of spin Hall angle and characteristic length, which we refer to as the spin conversion efficiency ξ , is

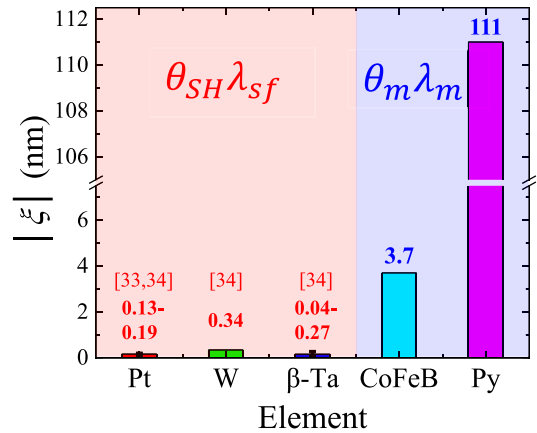


FIG. 4. The spin conversion efficiency ξ in different materials. The red-shaded area represents $\xi = \theta_{SH} \lambda_{sf}$ in typical heavy metals such as Pt (red), W (green), and β -Ta (dark blue) and the blue-shaded area represents $\xi = \theta_m \lambda_m$ in CoFeB (cyan) and Py (magenta).

often used as a figure of merit [33,34] to show how efficient a flow of spin angular momentum can be converted into a charge current. As shown in Fig. 4, the multiplication $\theta_m \lambda_m$ in CoFeB and Py measured here is orders higher than the $\theta_{\text{SH}} \lambda_{\text{sf}}$ in typical heavy metals such as Pt, W, and β -Ta. Therefore, our findings will also help accelerate the development of spin-based energy harvesting devices.

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S. C. M., P. H. W., S. Y. H., X. F., and D. Q. conceptualized the project. S. C. M. fabricated the thin film samples. S. C. M. and C. W. C. conducted the electrical transport measurements. X. F. developed the theoretical model. S. C. M. and D. Q. drafted the original manuscript. P. H. W., S. Y. H., and X. F. reviewed and revised the manuscript with contributions from all.

Data availability—The data are not publicly available. The data are available from the authors upon reasonable request.

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