

RESEARCH ARTICLE | JUNE 12 2025

Néel vector rotation driven by spin-orbit torque in amorphous ferrimagnetic GdCo

Tetsuma Mandokoro ; Yoichi Shiota  ; Tomoya Itoh; Hiroki Matsumoto ; Hideki Narita ; Ryusuke Hisatomi ; Shutaro Karube ; Teruo Ono  



Appl. Phys. Lett. 126, 232406 (2025)

<https://doi.org/10.1063/5.0270084>



View
Online



Export
Citation

Articles You May Be Interested In

Compositional dependence of spintronic properties in Pt/GdCo films

Appl. Phys. Lett. (September 2023)

Nonlinear response of hybrid magnons in synthetic antiferromagnets

Appl. Phys. Lett. (February 2025)

Surface versus bulk magnetization curves in amorphous GdCo cosputtered in the presence of oxygen

Appl. Phys. Lett. (May 1984)

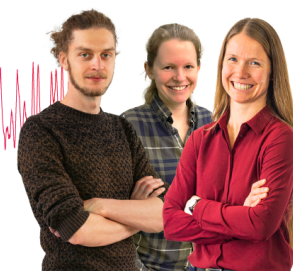
Webinar From Noise to Knowledge

May 13th – Register now



Zurich
Instruments

Universität
Konstanz



Néel vector rotation driven by spin-orbit torque in amorphous ferrimagnetic GdCo

Cite as: Appl. Phys. Lett. **126**, 232406 (2025); doi: [10.1063/5.0270084](https://doi.org/10.1063/5.0270084)

Submitted: 10 March 2025 · Accepted: 28 May 2025 ·

Published Online: 12 June 2025



View Online



Export Citation



CrossMark

Tetsuma Mandokoro,¹ Yoichi Shiota,^{1,2,a)} Tomoya Itoh,¹ Hiroki Matsumoto,¹ Hideki Narita,¹ Ryusuke Hisatomi,^{1,2} Shutaro Karube,^{1,2} and Teruo Ono^{1,2,a)}

AFFILIATIONS

¹Institute for Chemical Research, Kyoto University, Uji, Kyoto 611-0011, Japan

²Center for Spintronics Research Network, Kyoto University, Uji, Kyoto 611-0011, Japan

^{a)}Authors to whom correspondence should be addressed: shiota-y@scl.kyoto-u.ac.jp and ono@scl.kyoto-u.ac.jp

ABSTRACT

Spin superfluidity, a phenomenon enabling low-dissipative spin transport, has remained a theoretical concept. To realize spin superfluidity in an antiferromagnet, it is necessary to excite a Néel vector rotation within the magnetic easy-plane, which has been elusive so far due to the large magnetocrystalline anisotropy of antiferromagnets. In this study, we demonstrated spin-orbit torque-driven Néel vector rotation in amorphous ferrimagnetic GdCo. A pseudo-magnetic easy-plane is formed in a spin-flop state under an external magnetic field in the vicinity of the magnetization compensation temperature, and we observed stochastic binary switching in the anomalous Hall resistance, directly attributed to Néel vector rotation. Furthermore, homodyne detection confirmed rotation frequencies in the GHz range as expected from atomic spin simulations, providing evidence of dynamic Néel vector behavior. These findings demonstrate the continuous rotation of Néel vector driven by spin-orbit torque.

Published under an exclusive license by AIP Publishing. <https://doi.org/10.1063/5.0270084>

Efficient spin transport with minimal energy dissipation has become a focus in spintronics due to its potential to revolutionize information technologies. Compared to spin currents mediated by conduction electrons or spin waves, “spin superfluidity”—a quantum phenomenon characterized by low-dissipative spin current—stands out as a promising candidate.^{1,2} Analogous to superfluidity in liquid helium and superconductivity in electronic systems, spin superfluidity offers the possibility of transmitting spin angular momentum over macroscopic distances without significant loss.^{1,2}

In magnetic systems, spin superfluidity is achieved by maintaining a rotation of magnetization through a steady injection of angular momentum.^{1,3–9} In ferromagnets, dipolar interactions dramatically affect spin transport longer than the exchange coupling length, resulting in a disruption of spin superfluidity over long distances.^{3,6} Instead, antiferromagnets are promising for spin superfluidity because they have no net magnetization and are not affected by long-range dipolar interactions.^{10–14} Achieving spin superfluidity in antiferromagnets requires a rotation of the Néel vector within a magnetic easy-plane while maintaining a fixed net magnetization,^{4,6,9} as shown in Fig. 1. When spin currents are injected into an easy-plane antiferromagnet, where the spin polarization direction is orthogonal to the magnetic easy-plane, spin injection can cause the local magnetic moments to tilt

slightly out of the easy-plane. This tilt generates an internal antiferromagnetic exchange field, which drives the Néel vector to rotate within the magnetic easy-plane at frequencies adjustable by the current.^{3,4} As a related prior study on Néel vector rotation, chiral-spin rotation induced by spin-orbit torque (SOT) in chiral antiferromagnetic Mn₃Sn has been detected by the fluctuation of AHE resistance¹⁵ or the rectification effect due to frequency modulation of chiral-spin rotation by microwave currents.¹⁶ In addition, there exist many reports on the control of the Néel vector by SOT, such as switching of the Néel vector between stable states through the application of two currents or with the assistance of an external magnetic field.^{15–25} However, direct observation of the continuous rotation of the Néel vector in collinear antiferromagnets has been lacking so far due to experimental challenges, such as pinning by magnetocrystalline anisotropy within the easy-plane.

In this study, we investigate the dynamics of the Néel vector rotation in amorphous compensated ferrimagnet GdCo, which offers several advantages as a promising platform for easy-plane antiferromagnets.²⁶ First, its amorphous structure eliminates the intrinsic crystalline magnetic anisotropy, reducing the threshold current required to drive the spin dynamics. Second, in the vicinity of the magnetization compensation temperature, a spin-flop state is induced under relatively

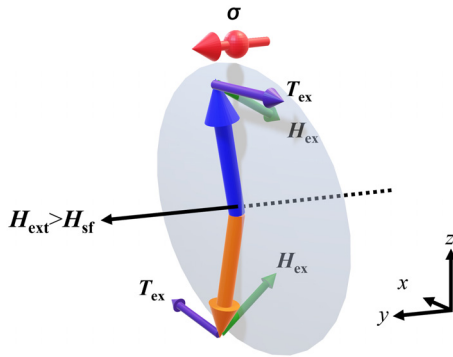


FIG. 1. The blue and orange arrows represent the local magnetic moments of two sublattices in ferrimagnet. These magnetic moments are fixed in a pseudo-magnetic easy-plane due to spin-flop transition under the conditions in which the external magnetic field H_{ext} is larger than the spin-flop field H_{sf} . The injected spin angular momentum σ denoted by the red sphere with arrow causes the local magnetic moments to tilt slightly out of the easy-plane. This tilt generates an internal antiferromagnetic exchange field H_{ex} , which exerts an exchange torque T_{ex} to rotate the Néel vector within the magnetic easy-plane.

low magnetic fields, forming a pseudo-magnetic easy-plane.^{27,28} Third, previous studies have shown that GdCo enables highly efficient spin manipulation through the SOT.^{29–31} Leveraging these properties of ferrimagnetic GdCo, we prepared a trilayer structure consisting of Ta/GdCo/Pt and observed stochastic binary switching in anomalous Hall resistance after the application of a 10- μs current pulse, directly attributed to the Néel vector rotation. Furthermore, homodyne detection, which measures the rectified Hall voltage arising from coupling between microwave currents and the Néel vector rotation, revealed GHz-range rotation frequencies. These results

mark a significant step in utilizing spin superfluidity in antiferromagnetic systems.

Thin films of Ta(5 nm)/Gd_{0.28}Co_{0.72}(3 nm)/Pt(5 nm) were deposited on a thermally oxidized Si substrate by dc magnetron sputtering. The GdCo alloy layer was formed by co-sputtering of Gd and Co targets, and the composition of GdCo was controlled by the sputtering power for each element. Ta and Pt layers prevent oxidation from the substrate and the atmosphere, respectively, and serve as spin injection sources due to large charge-to-spin conversion.^{31–35} Figure 2(a) shows an optical microscope image of the device structure. The films were patterned into a Hall device with a cross shape by photolithography and Ar ion milling, followed by the deposition of SiO₂ with a thickness of 17.5 nm to avoid contact between the device edge and the atmosphere. The width and length of the channel of the Hall device were 4 and 10 μm , respectively, and those of the Hall probe were 4 and 40 μm . The contact electrode of Ti(5 nm)/Au(80 nm) was then patterned by using photolithography and liftoff process.

We first characterized the magnetization compensation temperature and the spin-flop transition via anomalous Hall effect (AHE) measurements using the measurement setup shown in Fig. 2(a). In the case of ferrimagnets composed of transition metals (TMs) and rare earths (REs), the magnetotransport properties are mainly contributed by the TM material,^{28,29,31,36} which is Co in this study. Figure 2(b) shows the AHE resistance R_{xy} measurements under the magnetic field (H_{ext}) swept along the y -direction. Hysteresis loops were observed due to a slight out-of-plane component in the magnetic field. Considering the results obtained from applying the magnetic field in the z -direction, the magnetic easy-axis of the GdCo alloy layer is perpendicular (see also the AHE hysteresis loops under the out-of-plane component magnetic field in [supplementary material](#) Fig. S1). The branching of R_{xy} observed at 280 K is due to randomness in the Co magnetization configuration—either upward or downward—after the spin-flop

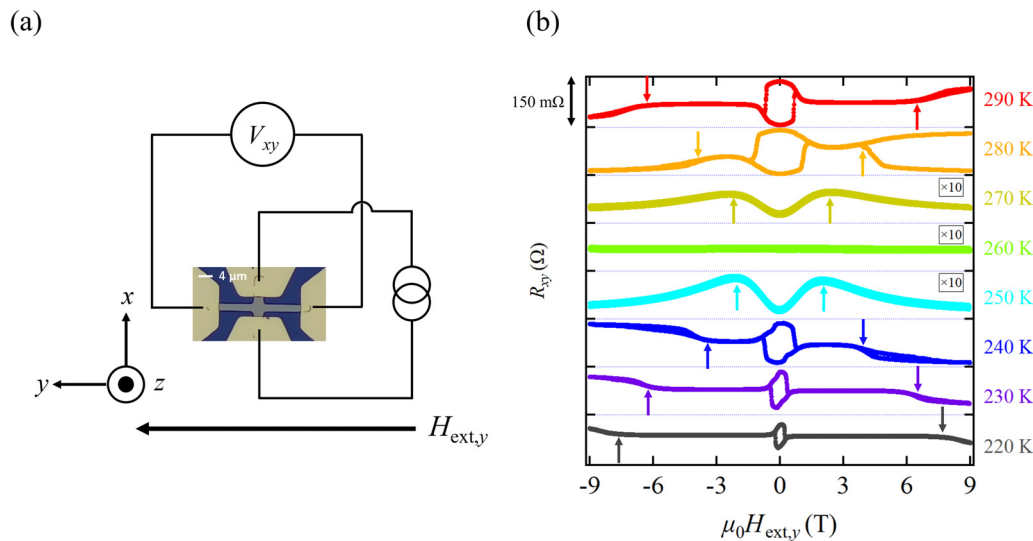


FIG. 2. (a) Schematic illustration of the device and measurement setup. The directions of the electric current and the magnetic field are x - and y -directions, respectively. (b) The hysteresis loops of AHE resistance R_{xy} from 220 to 290 K when 1 mA was applied. The arrows indicate the spin-flop field at each temperature. The spin-flop field was determined by the peak for 250 and 270 K, and by inflection points for other temperatures. The spin-flop field of 260 K cannot be determined because the value of the AHE resistance is almost constant.

transition. The hysteresis loops reverse polarity at the magnetization compensation temperature T_M , which was determined to be 260 K. After the dominant sublattice magnetization saturated in the magnetic field direction, the bending of the AHE resistance was observed at specific magnetic fields [arrows in Fig. 2(b)]. These fields correspond to the spin-flop field H_{sf} , which reaches a minimum value near T_M . In the range of 250–270 K, the magnetization could begin to spin-flop in almost zero magnetic field. Therefore, no clear hysteresis was obtained. The decrease in R_{xy} is thought to be caused by increase in the canting of the spin-flopped magnetization. This observation is consistent with the formula $H_{sf} = \lambda|M_{RE} - M_{TM}|$,^{37,38} where $M_{TM/RE}$ and λ represent the magnetization of TM/RE sublattice and antiferromagnetic exchange interaction constant between TM and RE, respectively (see [supplementary material](#) Fig. S2). The magnetizations of Co and Gd after the spin-flop transition are oriented in the out-of-plane direction due to perpendicular magnetic anisotropy and the gradual increase in AHE resistance indicates an inhomogeneity of the amorphous GdCo alloy film. The polarity reversal of hysteresis loops and the spin-flop transitions were also confirmed by the AHE hysteresis loops under the out-of-plane magnetic field, as shown in [supplementary material](#) Fig. S1. To summarize these results, the spin-flopped ferrimagnet, which can be regarded as the easy-plane antiferromagnet, can be obtained above the external magnetic field of 8 T or higher in the temperature range between 220 and 290 K.

Next, we studied the Néel vector's response to the induction of SOT under the spin-flop state of the GdCo alloy layer. In the experiment, the external magnetic field sufficient to induce spin-flop states was first applied in the in-plane direction, parallel to the spin current polarization, at a temperature near T_M . A pulsed current with a width of 10- μ s and a current of 11–20 mA (corresponding to a current density of 2.12×10^{11} – 3.85×10^{11} A/m²) was then applied to excite the Néel vector rotation. This pulsed current induces the SOT from the adjacent Pt and Ta layers into the GdCo alloy layer. Finally, the AHE

resistance was measured by applying a direct current of 1 mA, which is small enough not to excite the rotation. Here, we emphasize that in the spin-flop states, the Néel vector is kept almost collinear with the Co magnetization and both are in the out-of-plane direction in equilibrium. The sign change of the AHE resistivity indicates a 180° rotation of the Co magnetization and the same rotation of the Néel vector, which allows us to argue the SOT-induced rotation of the Néel vector as detailed below.

Figure 3 shows the AHE resistance R_{xy} measurements after applying the pulsed current for various system temperatures and current amplitudes under a magnetic field of 8 T or 9 T. At 220 K, the R_{xy} signals remain stable regardless of the applied current because the magnetic field is insufficient for all the spins to undergo a spin-flop transition or the applied current does not reach the threshold required for the excitation of Néel vector rotation. On the other hand, changes in R_{xy} signal corresponding to reversal of the Néel vector are observed between 230 and 260 K. This stochastic binary switching is most pronounced at higher currents and at temperature near T_M . This can be understood as follows. When the pulsed current exceeds a threshold of the potential, such as magnetic anisotropy, the Néel vector rotates during the pulsed current application and eventually relaxes along the out-of-plane direction, pointing randomly either upward or downward. Therefore, the observations of stochastic binary switching imply the Néel vector rotation driven by the SOT. It should be noted that at 260 K, the R_{xy} signal occasionally takes intermediate resistance values. This is because the net magnetization is entirely compensated at 260 K and the magnetization can point in directions other than the out-of-plane direction.^{39,40} In fact, intermediate resistance values were observed only in the vicinity of T_M during flipping of the Néel vector, as shown in [supplementary material](#) Fig. S1(b).

No significant switching above 270 K is likely due to temperature rise caused by Joule heating during pulse application. As shown in [supplementary material](#) Fig. S4, the temperature rises to around 300 K

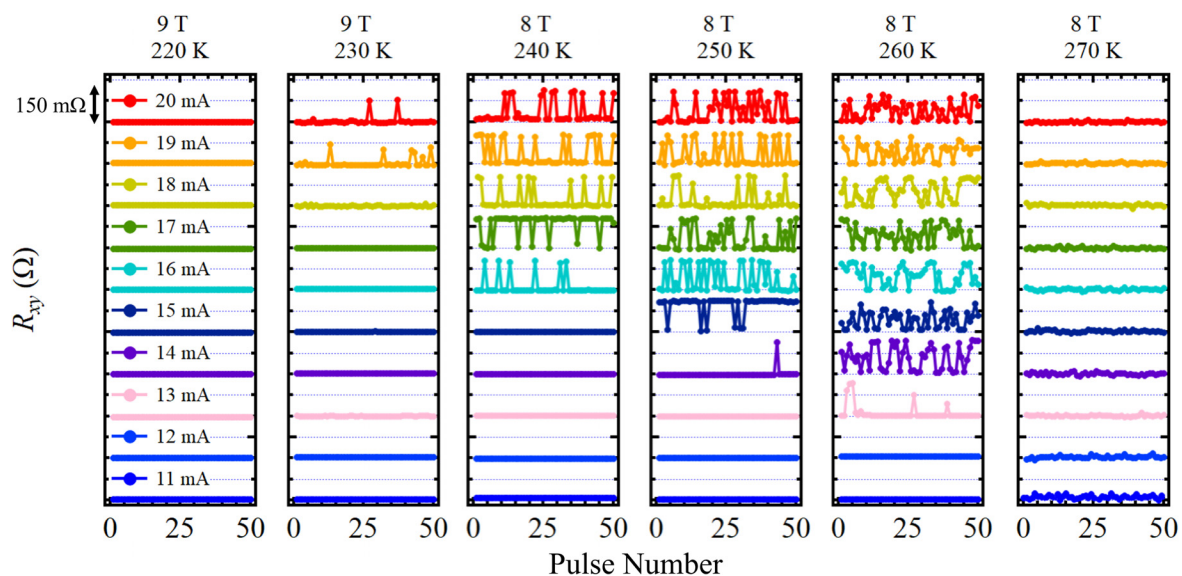


FIG. 3. The AHE resistance R_{xy} measured after 10- μ s pulsed currents of various current amplitudes were applied. The applied external magnetic field along y-direction and the system temperature are denoted at the top of each graph.

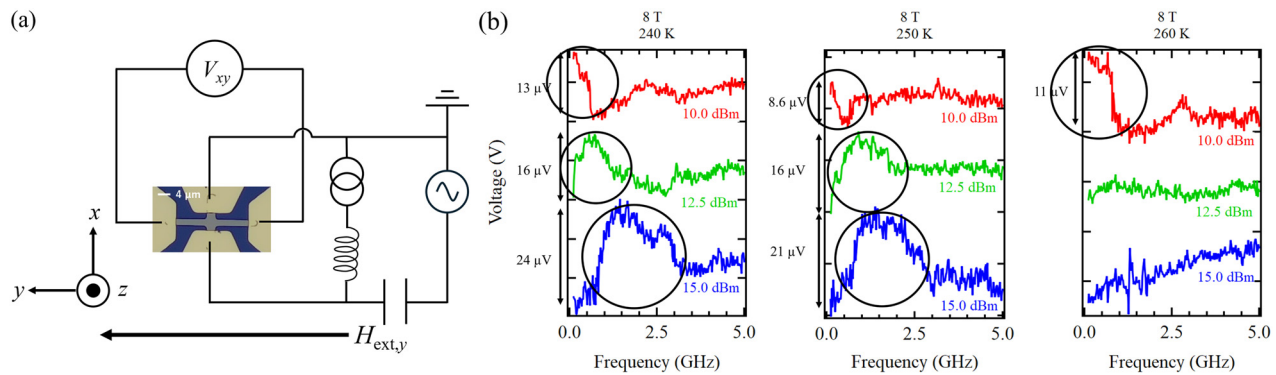


FIG. 4. (a) Schematic illustration of the measurement setup for homodyne detection through the anomalous Hall effect. (b) The rectified Hall voltage as a function of microwave frequency for various microwave power. The applied external magnetic field along the y -direction and the system temperature are denoted at the top of each graph. Circles indicate the resonance peaks attributed to the Néel vector rotation.

at a pulse amplitude of 20 mA, where the spin-flop state is released, and the Néel vector no longer rotates. In addition, the Néel vector rotation induced by SOT cannot be observed when the magnetic field is too small to induce the spin-flop state (see [supplementary material Fig. S3](#)).

To confirm the rotation frequency of the Néel vector rotation, a homodyne detection through the AHE was employed.^{41,42} In this measurement, a Hall device fabricated from films cut from the same wafer as in the above experiments was used. Schematic of the measurement setup for the homodyne detection is shown in [Fig. 4\(a\)](#). We applied a bias current to excite the Néel vector rotation and a microwave current to detect the rotation frequency through a bias tee. Amplitude of the bias current was set to be 20 mA, which is enough to excite the Néel vector rotation at a temperature near T_M . To enhance the signal-to-noise ratio and to reduce Joule heating, the bias current was applied as a square waveform with a frequency of 50 kHz, and rectified Hall voltage was measured using a lock-in amplifier. To eliminate the non-resonant background signal, the resulting spectra were obtained by subtracting the data measured under 0 T from that under 8 T.

[Figure 4\(b\)](#) shows the rectified Hall voltage as a function of microwave frequency for various microwave power at 240, 250, and 260 K, respectively. For the results of 240 and 250 K, distinct peaks appear at around 1–2 GHz. The peak amplitude increases with increasing microwave power, which indicates that the resonance peak originates from the rectified signal of Néel vector rotation. The rotation frequency of the Néel vector is determined by the magnitude of the applied SOT and thus depends on the current value. The rotation frequencies observed in the experiments are in good agreement with the simulation results (see [supplementary material S5](#)). We also find that the peak frequency shifts toward higher frequencies as the microwave power increases. This shift could be attributed to an additional SOT from the microwave current and Joule heating at higher power. When the rotation is disturbed and momentarily stops due to falling below the threshold current, the center of peaks shifts to a higher frequency. Joule heating raises the device temperature closer to T_M and consequently reduces the threshold current required to excite the Néel vector rotation. These factors explain the peak shift toward higher frequencies with increasing microwave power; however, further experiments are required to elucidate the mechanism in more detail. At

260 K, the peak disappeared above 12.5 dBm. This result corresponds to the fact that the stochastic binary switching of the anomalous Hall resistance disappeared above 270 K since $H_{\text{ext}} < H_{\text{sf}}$. In addition, no peaks were observed in the Hall voltage measurement under conditions of smaller bias current (5 mA), lower microwave power (0 dBm), smaller external magnetic field (0.1 T), or lower temperature (10 K), as shown in [supplementary material Fig. S6](#). From these observations, we confirm that the observed peaks result from the coupling between the Néel vector rotation and the applied microwave currents, and the frequency of Néel vector rotation is in the range of around 1–2 GHz.

In summary, we have demonstrated the excitation of Néel vector rotation by SOT in spin-flopped ferrimagnetic GdCo alloy thin films. We revealed that the threshold current required for the Néel vector rotation depends on temperature, as evidenced by the stochastic binary changes in the Hall resistance by the application of a 10- μ s pulsed current. Furthermore, we confirmed the rotation frequency of the Néel vector to be around 1–2 GHz from homodyne detection measurements, where coupling between the Néel vector rotation and the microwave currents results in the rectified Hall voltage. In addition, the frequencies and threshold current values obtained in the experiments show good agreement with the simulated results. Our study provides a crucial advancement toward realizing spin superfluidity for low-dissipative spin transport.

See the [supplementary material](#) for more details on the temperature dependence of AHE hysteresis loops under out-of-plane magnetic field, temperature dependence of spin-flop field, control experiments of stochastic binary switching, estimation of temperature rise due to the Joule heating effect, simulation of Néel vector rotation driven by spin-orbit torque, and control experiments of homodyne measurements.

The authors express gratitude to Se Kwon Kim for valuable discussion. This work was partially supported by JSPS KAKENHI (JP20H05665, JP21K18145, JP24H00007, JP22H01936, and JP24H02233), MEXT Initiative to Establish Next-generation Novel Integrated Circuits Centers (X-NICS) Grant No. JPJ011438, and the Collaborative Research Program of the Institute for Chemical Research, Kyoto University.

AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Tetsuma Mandokoro: Data curation (lead); Formal analysis (lead); Investigation (lead); Methodology (equal); Resources (equal); Software (lead); Validation (lead); Visualization (lead); Writing – original draft (lead); Writing – review & editing (equal). **Yoichi Shiota:** Conceptualization (equal); Funding acquisition (equal); Methodology (equal); Project administration (equal); Resources (equal); Supervision (equal); Writing – original draft (equal); Writing – review & editing (equal). **Tomoya Itoh:** Methodology (equal); Writing – review & editing (equal). **Hiroki Matsumoto:** Writing – review & editing (equal). **Hideki Narita:** Writing – review & editing (equal). **Ryusuke Hisatomi:** Writing – review & editing (equal). **Shutaro Karube:** Writing – review & editing (equal). **Teruo Ono:** Conceptualization (lead); Funding acquisition (lead); Resources (lead); Supervision (lead); Writing – original draft (equal); Writing – review & editing (equal).

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

REFERENCES

- ¹B. I. Halperin and P. C. Hohenberg, *Phys. Rev.* **188**, 898–918 (1969).
- ²E. B. Sonin, *Adv. Phys.* **59**, 181–255 (2010).
- ³S. Takei and Y. Tserkovnyak, *Phys. Rev. Lett.* **112**, 227201 (2014).
- ⁴S. Takei, B. I. Halperin, A. Yacoby, and Y. Tserkovnyak, *Phys. Rev. B* **90**, 017023 (2014).
- ⁵H. Skarsvåg, C. Holmqvist, and A. Brataas, *Phys. Rev. Lett.* **115**, 237201 (2015).
- ⁶E. B. Sonin, *Phys. Rev. B* **95**, 144432 (2017).
- ⁷C. Sun, T. Nattermann, and V. L. Pokrovsky, *Phys. Rev. Lett.* **116**, 257205 (2016).
- ⁸H. Chen, A. D. Kent, A. H. MacDonald, and I. Sodemann, *Phys. Rev. B* **90**, 220401 (2014).
- ⁹A. Qaiumzadeh, H. Skarsvåg, C. Holmqvist, and A. Brataas, *Phys. Rev. Lett.* **118**, 137201 (2017).
- ¹⁰W. Yuan, Q. Zhu, T. Su, Y. Yao, W. Xing, Y. Chen, Y. Ma, X. Lin, J. Shi, R. Shindou, X. C. Xie, and W. Han, *Sci. Adv.* **4**, eaat1098 (2018).
- ¹¹J. R. Hortensius, D. Afanasiev, M. Matthiesen, R. Leenders, R. Citro, A. V. Kimel, R. V. Mikhaylovskiy, B. A. Ivanov, and A. D. Caviglia, *Nat. Phys.* **17**, 1001–1006 (2021).
- ¹²A. E. Kanj, O. Gomonay, I. Boverter, P. Bortolotti, V. Cros, A. Anane, and R. Lebrun, *Sci. Adv.* **9**, eadh1601 (2023).
- ¹³R. Lebrun, A. Ross, S. A. Bender, A. Qaiumzadeh, L. Baldrati, J. Cramer, A. Brataas, R. A. Duine, and M. Kläui, *Nature* **561**, 222–225 (2018).
- ¹⁴H. Wang, R. Yuan, Y. Zhou, Y. Zhang, J. Chen, S. Liu, H. Jia, D. Yu, J. Ansermet, C. Song, and H. Yu, *Phys. Rev. Lett.* **130**, 096701 (2023).
- ¹⁵Y. Takeuchi, Y. Yamane, J. Y. Yoon, R. Itoh, B. Jinnai, S. Kanai, J. Ieda, S. Fukami, and H. Ohno, *Nat. Mater.* **20**, 1364–1370 (2021).
- ¹⁶S. Sakamoto, T. Nomoto, T. Higo, Y. Hibino, T. Yamamoto, S. Tamaru, Y. Kotani, H. Kosaki, M. Shiga, D. N. Hamane, T. Nakamura, T. Nozaki, K. Yakushiji, R. Arita, S. Nakatsuji, and S. Miwa, *Nat. Nanotechnol.* **20**, 216–221 (2025).
- ¹⁷L. Han, X. Fu, X. Cheng, J. Dai, L. Liu, Y. Li, Y. Zhang, W. Zhu, H. Bai, Y. Zhou, S. Liang, C. Chen, Q. Wang, X. Chen, L. Yang, Y. Zhang, C. Song, J. Liu, and F. Pan, *Sci. Adv.* **10**, eadn0479 (2024).
- ¹⁸W. He, T. Zhang, Y. Zhou, C. Wan, H. Wu, B. Cui, J. Xia, R. Zhang, T. Guo, P. Chen, M. Zhao, L. Jiang, A. Grutter, P. P. Balakrishnan, A. J. Caruana, C. J. Kinane, S. Langridge, G. Yu, C. Song, and X. Han, *Nat. Electron.* **7**, 975–983 (2024).
- ¹⁹C. Schmitt, A. Rajan, G. Beneke, A. Kumar, T. Sparmann, H. Meer, B. Bednarz, R. Ramos, M. A. Niño, M. Foerster, E. Saitoh, and M. Kläui, *Nano Lett.* **24**, 1471–1476 (2024).
- ²⁰P. Zhang, C. T. Chou, H. Yun, B. C. McGoldrick, J. T. Hou, K. A. Mkhoyan, and L. Liu, *Phys. Rev. Lett.* **129**, 017203 (2022).
- ²¹S. Reimers, Y. Lytvynenko, Y. R. Niu, E. Golias, B. Sarpi, L. S. I. Veiga, T. Denneulin, A. Kovács, R. E. D. Borkowski, J. Bläßer, M. Kläui, and M. Jourdan, *Nat. Commun.* **14**, 1861 (2023).
- ²²S. Y. Bodnar, L. Šmejkal, I. Turek, T. Jungwirth, O. Gomonay, J. Sinova, A. A. Sapozhnik, H. J. Elmers, M. Kläui, and M. Jourdan, *Nat. Commun.* **9**, 348 (2018).
- ²³P. Wadley, B. Howells, J. Železný, C. Andrews, V. Hills, R. P. Campion, V. Novák, K. Olejník, F. Maccherozzi, S. S. Dhesi, S. Y. Martin, T. Wagner, J. Wunderlich, F. Freimuth, Y. Mokrousov, J. Kuneš, J. S. Chauhan, M. J. Grzybowski, A. W. Rushforth, K. W. Edmonds, B. L. Gallagher, and T. Jungwirth, *Science* **351**, 587–590 (2016).
- ²⁴G. Q. Yan, S. Li, H. Lu, M. Huang, Y. Xiao, L. Wernert, J. A. Brock, E. E. Fullerton, H. Chen, H. Wang, and C. R. Du, *Adv. Mater.* **34**, 2200327 (2022).
- ²⁵T. Higo, K. Kondou, T. Nomoto, M. Shiga, S. Sakamoto, X. Chen, D. N. Hamane, R. Arita, Y. Otani, S. Miwa, and S. Nakatsuji, *Nature* **607**, 474–479 (2022).
- ²⁶S. K. Kim, G. S. D. Beach, K. J. Lee, T. Ono, T. Rasing, and H. Yang, *Nat. Mater.* **21**, 24–34 (2022).
- ²⁷D. H. Suzuki, B. H. Lee, and G. S. D. Beach, *Appl. Phys. Lett.* **123**, 122401 (2023).
- ²⁸T. Fu, S. Li, X. Feng, Y. Cui, J. Yao, B. Wang, J. Cao, Z. Shi, D. Xue, and X. Fan, *Phys. Rev. B* **103**, 064432 (2021).
- ²⁹K. Ueda, M. Mann, P. W. P. De Brouwer, D. Bono, and G. S. D. Beach, *Phys. Rev. B* **96**, 064410 (2017).
- ³⁰W. Seung Ham, S. Kim, D. H. Kim, K. J. Kim, T. Okuno, H. Yoshikawa, A. Tsukamoto, T. Moriyama, and T. Ono, *Appl. Phys. Lett.* **110**, 242405 (2017).
- ³¹T. Lee, J. Kim, S. An, S. Jeong, D. Lee, D. Jeong, N. J. Lee, K. S. Lee, C. Y. You, B. G. Park, K. J. Kim, S. Kim, and S. Lee, *Acta. Mater.* **246**, 118705 (2023).
- ³²A. Manchon, J. Železný, I. M. Miron, T. Jungwirth, J. Sinova, A. Thiaville, K. Garello, and P. Gambardella, *Rev. Mod. Phys.* **91**, 035004 (2019).
- ³³L. Liu, O. J. Lee, T. J. Gudmundsen, D. C. Ralph, and R. A. Buhrman, *Phys. Rev. Lett.* **109**, 096602 (2012).
- ³⁴L. Liu, T. Moriyama, D. C. Ralph, and R. A. Buhrman, *Phys. Rev. Lett.* **106**, 036601 (2011).
- ³⁵S. Woo, M. Mann, A. J. Tan, L. Caretta, and G. S. D. Beach, *Appl. Phys. Lett.* **105**, 212404 (2014).
- ³⁶N. Nagaosa, J. Sinova, S. Onoda, A. H. MacDonald, and N. P. Ong, *Rev. Mod. Phys.* **82**, 1539–1592 (2010).
- ³⁷A. E. Clark and E. Callen, *J. Appl. Phys.* **39**, 5972–5982 (1968).
- ³⁸R. J. Radwanski, *Physica B+C* **142**, 57–64 (1986).
- ³⁹Q. Liu, L. Zhu, X. S. Zhang, D. A. Muller, and D. C. Ralph, *Appl. Phys. Rev.* **9**, 021402 (2022).
- ⁴⁰T. Xu, Y. Cheng, Y. Dong, H. Bai, H. A. Zhou, X. Shu, P. Gargiani, M. Valdivares, P. Yu, and W. Jiang, *Phys. Rev. Appl.* **19**, 021402 (2023).
- ⁴¹J. C. Sankey, P. M. Braganca, A. G. F. Garcia, I. N. Krivorotov, R. A. Buhrman, and D. C. Ralph, *Phys. Rev. Lett.* **96**, 227601 (2006).
- ⁴²A. A. Tulapurkar, Y. Suzuki, A. Fukushima, H. Kubota, H. Maehara, K. Tsunekawa, D. D. Djayaprawira, N. Watanabe, and S. Yuasa, *Nature* **438**, 339–342 (2005).