



HOKKAIDO UNIVERSITY

Title	Sign reversal of current-induced torque in perpendicularly magnetized Pd/Co ₂ MnGa and Pd/Co ₂ MnSi
Author(s)	Koyama, Takaya; Uemura, Tetsuya; Yamanouchi, Michihiko
Citation	Applied Physics Letters, 128(26), 262405 https://doi.org/10.1063/5.0331050
Issue Date	2026-06-29
Doc URL	https://hdl.handle.net/2115/100004
Rights	This article may be downloaded for personal use only. Any other use requires prior permission of the author and AIP Publishing. This article appeared in Appl. Phys. Lett. 128(26), 262405 (2026) and may be found at https://doi.org/10.1063/5.0331050 .
Type	journal article
File Information	Appl. Phys. Lett.128- 26_262405.pdf



Sign reversal of current-induced torque in perpendicularly magnetized Pd/Co₂MnGa and Pd/Co₂MnSi

Takaya Koyama¹, Tetsuya Uemura¹, and Michihiko Yamanouchi^{1,*}

¹Division of Electronics for Informatics, Graduate School of Information Science and Technology, Hokkaido University, Sapporo 060-0814, Japan

Abstract

We studied the effective magnetic field H_{eff} arising from the spin-orbit torque (SOT) and/or orbital torque (OT) by measuring shifts of out-of-plane hysteresis loops under various in-plane currents I_s and in-plane magnetic fields H_x along I in perpendicularly magnetized Pd/Co₂MnGa (CMG) and Pd/Co₂MnSi (CMS). The H_{eff} for Pd/CMS is explained well by the SOT originating from the spin Hall effect in Pd, whereas that for Pd/CMG points in the opposite direction under a given polarity of I and H_x . Neither the self-induced SOT in CMG nor the SOT originating from the interfaces is responsible for the H_{eff} reversing in Pd/CMG. The magnitude of the effective spin/orbital Hall angle, derived from the H_{eff} , increases with the thickness of both the CMG and Pd layers in Pd/CMG, which is consistent with the predicted behavior of the OT originating from the orbital Hall effect in Pd. Considering these results and the fact that CMG has stronger spin orbit interaction than CMS, the OT, which is larger than and opposite to the SOT originating from the SHE in Pd, is a plausible candidate for reversing the H_{eff} in Pd/CMG.

*Corresponding author: m-yama@ist.hokudai.ac.jp

Spintronics devices utilizing the orbital torque (OT)-induced magnetization switching have attracted much attention as key elements in next-generation memory and logic because they offer high-speed and energy-efficient operation. Since the OT is induced by the orbital current, ways to generate an orbital current have been intensively studied.¹⁻³ However, the orbital current does not directly exert torque on the magnetization, so it needs to be converted to the spin current to induce the OT.⁴ The OT has been studied in bilayer structures consisting of a ferromagnetic layer (FM) and a nonmagnetic metal layer (NM) and in trilayer structures in which a nonmagnetic heavy metal layer (HM) is inserted between the FM and NM. When an in-plane current is applied to such structures, orbital currents are typically generated from the NM and/or the interfaces and are converted into spin currents through the spin-orbit interaction (SOI) in the FM or HM.¹⁻⁸ Spin currents can also be generated through the SOI in the NM and HM and at the interfaces by applying the in-plane current,⁹ and both the orbital and spin currents are injected into the FM. Consequently, an effective torque, which is the combined torque of the OT and spin-orbit torque (SOT), acts on the magnetization, and its direction is even reversed depending on the relative direction and magnitude of the OT and SOT. The trilayer structures possess more sources generating current-induced torque, which is difficult to distinguish from the OT, and thus the bilayer structures are desirable for examining the OT. Since the orbital current needs to be converted to generate the OT but not to generate the SOT, the OT has generally been identified by comparing the effective torque induced in the structures having a weak SOI ferromagnet, where the OT is not important, with that under test conditions.^{4,5} Moreover, strong SOI ferromagnets used for generating the OT are mainly limited to Ni, rare-earth elements, and alloys containing them.²⁻⁷ Therefore, to properly understand the OT, the choice of ferromagnets with strong SOI for generating the OT needs to be expanded. Cobalt-based Heusler alloys Co_2MnX are suitable to study the OT and its dependence on the SOI because the strength of their SOI can be modulated by varying the element X.¹⁰ However, the OT in Co_2MnX has not yet been reported.

In this work, we focused on bilayer structures consisting of a Pd and a Co_2MnGa (CMG) or Co_2MnSi (CMS) to investigate the OT in them. CMG is a Weyl ferromagnet in the bulk state^{11,12} that

exhibits a short spin diffusion length comparable to Ni,^{13,14} indicating that CMG has relatively strong SOI. In contrast, CMS is a half-metal that exhibits weak SOI, and magnetic tunnel junctions containing CMS electrodes have demonstrated large tunnel magnetoresistance.^{15,16} A recent theoretical study predicts that the magnitude of the orbital Hall conductivity related to generation of the orbital current is comparable to that of the spin Hall conductivity in Pd,^{17,18} but the OT has not yet been observed in the structures having Pd. Moreover, depositing Pd onto CMG and CMS can make their magnetic easy axis perpendicular to the plane through the interface magnetic anisotropy,¹⁹ and the perpendicularly magnetized CMG and CMS enable the SOT and/or the OT (SOT/OT) to be evaluated by monitoring transverse resistance R_t reflecting the anomalous Hall effect proportional to the perpendicular component of magnetization. Here, we examine the current-induced magnetization switching and torque to investigate the OT in these structures.

Two types of bilayer structures consisting of Pd(2–4)/CMG(0.8–2.0) and Pd(3)/CMS(0.8), from the surface side, were deposited on MgO (001) substrates through a 10-nm-thick MgO buffer layer, where the numbers in parentheses are nominal film thicknesses in nm. After the MgO buffer was deposited by using electron-beam evaporation at 600°C, CMG or CMS was deposited by using magnetron sputtering at room temperature followed by annealing at 350°C for 1 hour. As shown in Figs. S1(a)-(d) of the supplementary material, reflection high-energy electron diffraction patterns of both CMG and CMS layers exhibited streaky diffraction patterns along the MgO[100] and MgO[110] directions (corresponding to the [100] and [110] directions of CMG or CMS, respectively^{20,21}) after the annealing, indicating epitaxial growth with relatively smooth surfaces. The presence of additional streaks between the bright fundamental streaks along the MgO[100] direction further suggests that both layers had a L2₁ structure. A Pd layer was subsequently deposited on them by using magnetron sputtering at room temperature, and then the bilayers were annealed at 325°C for 1 hour in a vacuum under an out-of-plane magnetic field of 0.5 T to make their magnetic easy axis perpendicular to the plane. After that, a Ta(1)/MgO(1) capping structure was deposited on the bilayers at room temperature. The resultant structures were processed into Hall bars with a 5-μm-wide channel in the [110] direction

of CMG or CMS and a pair of Hall probes by using conventional photolithography and Ar ion milling. Figure 1(a) shows a schematic of the device with the measurement setup and the definition of the Cartesian coordinate system.

The R_t was measured with a constant current $I = +100 \mu\text{A}$ while sweeping the out-of-plane magnetic field H_z at room temperature. Figure 1(b) and (c) show R_t as a function of $\mu_0 H_z$ for the Pd(3)/CMG(1.6) and Pd(3)/CMS(0.8), respectively, where μ_0 is the vacuum permeability. Both bilayers exhibited square hysteresis loops, which indicates that they were perpendicularly magnetized. The remanent value of R_t was six times larger for Pd/CMG than for Pd/CMS, which reflects the anomalous Hall conductivity being larger for CMG than for CMS.

We examined the SOT/OT-induced magnetization switching in the Pd(3)/CMG(1.6) and Pd(3)/CMS(0.8) by using R_t . After preparing the positive (negative) initial magnetization configurations by aligning the magnetization direction to the $+z$ ($-z$) direction with $\mu_0 H_z = 0.5 \text{ T}$ (-0.5 T) and then removing H_z to 0, a 100-ms current pulse I_{pulse} was applied to the channel under a constant in-plane magnetic field H_x in the x direction. Figure 2(a) (2(b)) shows R_t measured with $I = +100 \mu\text{A}$ after applying each I_{pulse} swept from an amplitude of -6 to $+6 \text{ mA}$ ($+6$ to -6 mA) under $\mu_0 H_x = -20 \text{ mT}$ ($+20 \text{ mT}$) for the negative (positive) initial magnetization configuration in Pd/CMG. Magnetization was observed to almost completely switch from negative to positive (positive to negative) when I_{pulse} was antiparallel (parallel) to H_x . Figure 2(c) (2(d)) shows R_t measured in a similar way to that in Fig. 2(a) and (b) as a function of I_{pulse} swept from an amplitude of $+7$ to -7 mA (-7 to $+7 \text{ mA}$) under $\mu_0 H_x = +50 \text{ mT}$ (-50 mT) for the positive (negative) initial magnetization configuration in Pd/CMS. Magnetization was almost completely switched at sufficiently large $|I_{\text{pulse}}|$, whereas the polarity of the $R_t - I_{\text{pulse}}$ loops for Pd/CMS was opposite to that for Pd/CMG under the given polarity of H_x .

We evaluated the current-induced effective magnetic field H_{eff} arising from the SOT/OT for the Pd(3)/CMG(1.6) and Pd(3)/CMS(0.8) by measuring shifts of the out-of-plane hysteresis loops under a constant I and H_x to investigate the driving mechanism for the current-induced magnetization

switching. The device and measurement setup used for this measurement were the same as those for the switching measurement. Figure 3(a) and 3(b) (3(c) and 3(d)) show R_t measured with $I = \pm 1.5$ (± 2.0) mA as a function of $\mu_0 H_z$ for Pd(3)/CMG(1.6) (Pd(3)/CMS(0.8)) under $\mu_0 H_x = +60$ and -60 mT, respectively. When I and H_x are parallel (antiparallel), the center of the hysteresis loop was shifted in the negative (positive) $\mu_0 H_z$ direction for Pd/CMG, whereas the center was shifted in the positive (negative) $\mu_0 H_z$ direction for Pd/CMS.

According to the conventional SOT model,²² the sign-reversed value of the shift amount corresponds to the H_{eff} arising from the SOT/OT exerted on domain walls created during the magnetization reversal. We performed measurements similar to those used to make Fig. 3(a)-(d) by applying various I s under various in-plane magnetic fields H_{in} s (H_x s or magnetic fields H_y s in the y direction) and evaluated the efficiency η of H_{eff} generation per current density J_{pd} in Pd. The values of η were determined by converting I into J_{pd} in the linear slope of the $\mu_0 H_{\text{eff}}$ versus I plots under each H_{in} , where the values of J_{pd} were calculated to be 82% and 90% of the total current for Pd(3)/CMG(1.6) and Pd(3)/CMS(0.8), respectively, assuming that current flows separately in accordance with the conductivity in each layer. The current flowing through the Pd layer was estimated by subtracting the contribution of a separately prepared CMG(1.6) (CMS(0.8)) single layer from the total current of the Pd/CMG(CMS). The obtained J_{pd} s thus represent lower limits, given the influence of current shunting. The obtained η are plotted as a function of $\mu_0 H_{\text{in}}$ for Pd(3)/CMG(1.6) and Pd(3)/CMS(0.8) in Fig. 3(e) and (f), respectively. For both structures, η varied approximately in proportion to H_x at the small $|H_x|$ and saturated at the large $|H_x|$, whereas η did not obviously vary with the application of H_y . These H_x and H_y dependences of η are consistent with what would be expected from the conventional SOT model, where the saturation of η with respect to H_x is attributed to the magnetization direction being realigned to the x -direction by large H_x in each domain wall created during magnetization reversal.²² The polarity of the $\eta - H_x$ curve for Pd/CMG was opposite to that for Pd/CMS, which is in line with the results of the switching measurements. These results indicate that the direction of the effective torque acting on the magnetization in Pd/CMG is opposite to that in

Pd/CMS. The saturated values of $|\eta|$ denoted as η_{sat} for Pd(3)/CMG(1.6) and Pd(3)/CMS(0.8) were determined to be $7.2 \times 10^{-15} \text{ Tm}^2\text{A}^{-1}$ and $8.4 \times 10^{-15} \text{ Tm}^2\text{A}^{-1}$, respectively. Note that these $|\eta|$ s correspond to upper limits, accounting for the above-mentioned current shunting. The direction of H_{eff} for Pd/CMS agrees with that caused by the SOT originating from the SHE reported in Pd,^{23,24} whereas that for Pd/CMG is opposite to it. We derived the effective spin/orbital Hall angle ζ^{eff} in Pd from the η_{sat} obtained for Pd/CMG and Pd/CMS to investigate the mechanism behind their H_{eff} . The ζ^{eff} is expressed as $\zeta^{\text{eff}} = 4eM t_{\text{FM}} \eta_{\text{sat}} / (\pi \mu_0 \hbar)$ by using η_{sat} , where $\hbar$, e , M , and t_{FM} are the reduced Planck constant, elementary charge, magnetization, and FM thickness, respectively. By substituting the η_{sat} for Pd/CMG (Pd/CMS) and $M = 0.56 \text{ T}$ (1.1 T) obtained from the magnetization measurements for a separately prepared Pd/CMG (Pd/CMS) under the same conditions as the present samples into this expression, ζ^{eff} for Pd(3)/CMG(1.6) and Pd(3)/CMS(0.8) are calculated to be -1.0% and 1.1% , respectively. The value of ζ^{eff} for Pd/CMS agrees well with the spin Hall angle in Pd previously determined by the nonlocal spin valve and spin pumping measurements,^{25,26} whereas that for Pd/CMG is similar in magnitude but opposite in sign. These results indicate that the SOT originating from the SHE in Pd governs the H_{eff} in Pd/CMS and that a current-induced torque, which is opposite to the SOT, makes the dominant contribution to the H_{eff} in Pd/CMG.

Given the H_{eff} for Pd/CMG pointed perpendicular to the plane under H_x , the possible candidates of the mechanisms for the H_{eff} in Pd/CMG are the SOTs (which originate from the Pd layer, the upper/lower interfaces of the CMG layer, and the CMG layer) and the OTs (which originate from the Pd layer and the interfaces between the layers consisting of the entire stack). We first examined the contribution of the SOTs to clarify the mechanism behind the H_{eff} in Pd/CMG. According to the positive spin Hall conductivity in Pd,^{17,18} the SOT originating from the SHE in the Pd layer should induce the H_{eff} opposite to the observed H_{eff} in the Pd/CMG, which indicates that it does not make the dominant contribution to the H_{eff} in the Pd/CMG. The SOT originating from the SOI at the interfaces of FM in the bilayer structures has two components (the field-like torque and the damping-like torque), and the former is usually much larger than the latter.²⁷ From the harmonic Hall voltage measurements

for Pd(3)/CMG(1.8), the H_{eff} caused by the field-like torque was evaluated to be less than 25% of that by the damping-like torque, and the direction of the latter H_{eff} was parallel to the H_{eff} obtained from the out-of-plane hysteresis measurements (see Fig. S2.2 in supplementary material). These results suggest that the SOT originating from the interfaces is not significant for the sign reversal of H_{eff} in Pd/CMG.

A previous study showed that a single CMG layer a few tens of nm thick generated the self-induced SOT originating from the interplay between the topological electronic states and the strain in CMG, and that its direction was reversed by changing the direction of electrical current from the [100] to [110] direction of CMG.²⁰ We evaluated the H_{eff} arising from the SOT/OT by measuring shifts of out-of-plane hysteresis loops under various I_s and H_x s for a Pd/CMG Hall bar with a channel in the [100] direction of CMG, which is denoted as Pd/CMG [100] hereafter. Figure 4(a) and (b) show R_t measured with $I = \pm 2.0$ mA as a function of $\mu_0 H_z$ under $\mu_0 H_x = +50$ and -50 mT respectively for the Pd(3)/CMG(1.6) [100]. The shift direction in the $R_t - \mu_0 H_z$ hysteresis loops, corresponding to the direction of the H_{eff} , with respect to I and H_x was the same as that for the Pd/CMG [110] as shown in Fig. 3(a) and (b). The Pd/CMG [100] exhibits $\mu_0 H_x$ dependence of η similar to Pd/CMG [110], as shown in Fig. 4(c), and the value of ζ^{eff} for Pd/CMG [100] derived from the η_{sat} in Fig. 4(c) matches that for Pd/CMG [110] within a 7% difference. The H_{eff} for Pd/CMG is mostly independent of the relative orientation of its crystal axis and I , which strongly suggests that the self-induced SOT originating from the topological electronic states is unimportant in the present Pd/CMG. Another self-induced SOT (the anomalous SOT), which was predicted in the ferromagnets with bulk inversion symmetry like CMG, was important in the ferromagnets with thicknesses larger than its exchange length.²⁸ However, it is also unimportant in the present Pd/CMG because its CMG (1.6 nm) was much smaller than the exchange length of CMG (approximately 13 nm²⁹). To further support these findings, we evaluated H_{eff} for a CMG(1.6) single layer by using the harmonic Hall voltage measurement (see Fig. S2.1 in supplementary material). The direction of the H_{eff} is opposite to that for Pd(3)/CMG(1.6), and thus the self-induced SOT is again not predominant in the present Pd/CMG. The interfacial spin

transparency can modify the SOT originating from the SHE in the Pd layer, thereby reversing the H_{eff} in Pd/CMG by altering the total SOT. However, considering the polarities of the Pd-induced and self-induced SOTs, along with the magnitude of the SOT originating from the interfaces, the interfacial spin transparency does not significantly contribute to the reversal of H_{eff} in Pd/CMG. Therefore, the above-mentioned conventional SOTs are ruled out from being the primary mechanism behind the H_{eff} in Pd/CMG.

Next, we examined the contribution of the OTs to the H_{eff} for Pd/CMG. The effective torque for Pd/CMS, whose CMS exhibits weaker SOI than CMG, is attributed to the SOT originating from the SHE in Pd. On the other hand, it has been reported that the effective torque for Pt/CMG was parallel to that for the present Pd/CMS, and that its effective spin Hall angle corresponding to the ζ^{eff} was comparable to that in bilayer structures consisting of Pt and conventional ferromagnets,³⁰ where the orbital Hall conductivity is much smaller than the spin Hall conductivity in Pt^{17,18} and its spin Hall conductivity has the same sign as that in Pd.^{17,18} Since the OT requires the orbital current to be converted to the spin current through the SOI, these results suggest that the OT, which is opposite to the SOT originating from the SHE in Pd, dominates the effective torque in Pd/CMG. If that is indeed the case, the sign reversal of the effective torque in Pd(3)/CMG(1.6) and Pd(3)/CMS(0.8) can be caused by the difference in the FM thickness through modulating the conversion efficiency from the orbital to spin current.⁷ To examine the effect of CMG thickness on the effective torque, we determined η for Pd(3)/CMG(0.8 – 2.0) by using the hysteresis loop shift measurements under various I_s and H_{xs} . These measurements were conducted at 250 K to enhance the perpendicular magnetic anisotropy for an accurate determination of H_{eff} . Figure 5(a) shows η as a function of $\mu_0 H_x$ for Pd/CMG with the CMG thicknesses of 0.8, 1.6, and 2.0 nm. The polarity of the $\eta - \mu_0 H_x$ curves was the same for all Pd/CMGs, which indicates that the sign of the H_{eff} is independent of CMG thickness with the studied range. Figure 5(b) summarizes the CMG thickness dependence of the ζ^{eff} evaluated from the η_{sat} in Fig. 5(a) and M obtained from the magnetization measurements. The magnitude of ζ^{eff} increases with increasing CMG thickness, which is consistent with the predicted dependence of the

OT on the ferromagnetic layer thickness. These results suggest that the sign reversal of H_{eff} is not caused by the difference in the FM thickness but by that in the strength of the SOI between CMG and CMS. Possible sources of the orbital current inducing the OT in Pd/CMG are the orbital Hall effect (OHE) in the Pd layer and/or the orbital Rashba–Edelstein effect at the interfaces between the layers consisting of the entire stack. We conducted the hysteresis loop shift measurements on Pd(2 – 4)/CMG(2.0) and examined the Pd thickness dependence of ξ^{eff} to clarify the origin of the current-induced torque at 250 K, a temperature selected to enhance the perpendicular magnetic anisotropy for an accurate determination of H_{eff} . The values of ξ^{eff} , determined from the $\eta - \mu_0 H_x$ curves in Fig. 5(c), are plotted as a function of Pd thickness in Fig. 5(d). The value of ξ^{eff} was negative, and its magnitude increased with increasing Pd thickness, which strongly suggests that the H_{eff} originates from the Pd layer rather than the interfaces. Furthermore, this finding is consistent with the predicted Pd-thickness dependence of the OT induced by the OHE in Pd.⁷ Previous theoretical studies have reported both positive³¹ and negative³² orbital Hall conductivities for Pd, and thus further theoretical support is required to determine the sign of the orbital-to-spin conversion efficiency in CMG. Although it is too early to draw a firm conclusion, the OT, originating primarily from the OHE in Pd, is a plausible candidate for the sign reversal of H_{eff} in Pd/CMG.

In summary, we studied the current-induced magnetization switching and the torque in Pd/CMG and Pd/CMS. Both Pd/CMG and Pd/CMS exhibited clear magnetization switching induced by SOT/OT, while the switching polarity was reversed in them under the given polarity of H_x . The H_{eff} arising from the SOT/OT for Pd/CMG and Pd/CMS were evaluated by measuring shifts of out-of-plane hysteresis loops under various I_s and H_x s. The H_x dependence of η for both Pd/CMG and Pd/CMS are consistent with what would be expected from the conventional SOT model, and the polarity of the $\eta - H_x$ curve for Pd/CMG was opposite to that for Pd/CMS, which is in line with the results of the switching measurements. These results indicate that the effective torque acting on the magnetization in Pd/CMG is opposite to that in Pd/CMS. The value of ξ^{eff} for Pd/CMS agrees well with the spin Hall angle in Pd, and thus the SOT originating from the SHE in Pd dominates the

effective torque in Pd/CMS. The SOTs originating from the Pd layer, the CMG layer, and the interfaces are not responsible for the effective torque reversing in Pd/CMG. The magnitude of ζ^{eff} for Pd/CMG increases with the thickness of both the CMG and Pd layers, which is consistent with the predicted behavior of the OT originating from the OHE in Pd. Considering these results and the fact that CMG has stronger SOI than CMS, the OT, which is larger than and opposite to the SOT originating from the SHE in Pd, is a plausible candidate for reversing the effective torque in Pd/CMG. The present work indicates that Cobalt-based Heusler alloys with different SOI strength provide a workbench for studying the OT and offer a pathway for developing efficient magnetization switching by tuning their SOI into spintronic devices.

Supplementary Material

See the supplementary material for the reflection high-energy electron diffraction patterns of the CMG and CMS layers, and the harmonic Hall voltage measurements for the CMG(1.6) single layer and the Pd(3)/CMG(1.8) bilayer.

Acknowledgements

This work was supported in part by JSPS KAKENHI (25K0127905), MEXT X-NICS (JPJ011438), MEXT ARIM (JPMXP1225HK0012), JST CREST (JPMJCR22C2), and JST SPRING (JPMJSP2119).

Author Declarations

Conflict of Interest

The authors have no conflicts to disclose.

Data Availability

This is the author's peer reviewed, accepted manuscript. However, the online version of record will be different from this version once it has been copyedited and typeset.

PLEASE CITE THIS ARTICLE AS DOI: 10.1063/5.0331050

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

This is the author's peer reviewed, accepted manuscript. However, the online version of record will be different from this version once it has been copyedited and typeset.

PLEASE CITE THIS ARTICLE AS DOI: 10.1063/5.0331050

References

1. R. Fukunaga, S. Haku, H. Hayashi and K. Ando. *Phys. Rev. Res.* **5**, 023054 (2023).
2. Y. Choi, D. Jo, K. Ko, D. Go, K. Kim, H. G. Park, C. Kim, B. Min, G. Choi and H. Lee. *Nature* **619**, 52–56 (2023).
3. S. Lee, M. Kang, D. Go, D. Kim, J. Kang, T. Lee, G. Lee, J. Kang, N. Jong Lee, Y. Mokrousov, S. Kim, K. Kim, K. Lee and B. Park, *Commun. Phys.* **4**, 234 (2021).
4. D. Lee, D. Go, H. Park, W. Jeong, H. Ko, D. Yun, D. Jo, S. Lee, G. Go, J. H. Oh, K. Kim, B. Park, B. Min, H. C. Koo, H. Lee, O. Lee and K. Lee, *Nat. Commun.* **12**, 6710 (2021).
5. Y. Yang, P. Wang, J. Chen, D. Zhang, C. Pan, S. Hu, T. Wang, W. Yue, C. Chen, W. Jiang, L. Zhu, X. Qiu, Y. Yao, Y. Li, W. Wang and Y. Jiang, *Nat. Commun.* **15**, 8645 (2024).
6. Y. Guo, Y. Zhang, W. Lv, B. Wang, B. Zhang and J. Cao, *Appl. Phys. Lett.* **123**, 022408 (2023).
7. H. Hayashi, D. Jo, D. Go, T. Gao, S. Haku, Y. Mokrousov, H. Lee and K. Ando, *Commun. Phys.* **6**, 32 (2023).
8. S. Ding, A. Ross, D. Go, L. Baldrati, Z. Ren, F. Freimuth, S. Becker, F. Kammerbauer, J. Yang, G. Jakob, Y. Mokrousov and M. Kläui, *Phys. Rev. Lett.* **125**, 177201 (2020).
9. L. Zhu, D. C. Ralph and R. A. Buhrman, *Appl. Phys. Rev.* **8**, 031308 (2021).
10. J. Tung and G. Guo *New J. Phys.* **15** 033014 (2013).
11. A. Sakai, Y. P. Mizuta, A. A. Nugroho, R. Sihombing, T. Koretsune, M. Suzuki, N. Takemori, R. Ishii, D. Nishio-Hamane, R. Arita, P. Goswami and S. Nakatsuji, *Nat. Phys.* **14**, 1119 (2018).
12. K. Sumida, Y. Sakuraba, K. Masuda, T. Kono, M. Kakoki, K. Goto, W. Zhou, K. Miyamoto, Y. Miura, T. Okuda and A. Kimura, *Commun. Mater.* **1**, 89 (2020).
13. L. Leiva, S. Granville, Y. Zhang, S. Dushenko, E. Shigematsu, T. Shinjo, R. Ohshima, Y. Ando and M. Shiraishi, *Phys. Rev. B* **103**, L041114 (2021).
14. K. Ko and G. Choi, *J. Magn. Magn. Mater.* **510**, 166945 (2020).
15. S. Ishida, S. Fujii, S. Kashiwagi and S. Asano, *J. Phys. Soc. Jpn.* **64**, 2152 (1995).

This is the author's peer reviewed, accepted manuscript. However, the online version of record will be different from this version once it has been copyedited and typeset.

PLEASE CITE THIS ARTICLE AS DOI: 10.1063/5.0331050

16. H. Liu, Y. Honda, T. Taira, K. Matsuda, M. Arita, T. Uemura and M. Yamamoto, Appl. Phys. Lett. **101**, 132418 (2012).
17. T. Tanaka, H. Kontani, M. Naito, T. Naito, D. S. Hirashima, K. Yamada and J. Inoue, Phys. Rev. B **77**, 165117 (2008).
18. D. Go, H. Lee, P. M. Oppeneer, S. Blügel and Y. Mokrousov, Phys. Rev. B **109**, 174435 (2024).
19. B. M. Ludbrook, B. J. Ruck and S. Granville, Appl. Phys. Lett. **110**, 062408 (2017).
20. M. Aoki, Y. Yin, S. Granville, Y. Zhang, N. V. Medhekar, L. Leiva, R. Ohshima, Y. Ando and M. Shiraishi, Nano Lett. **23**, 15 (2023).
21. G. Ortiz, A. García-García, N. Biziere, F. Boust, J. F. Bobo, E. Snoeck, J. Appl. Phys. **113**, 043921 (2013).
22. C.-F. Pai, M. Mann, A. J. Tan and G. S. D. Beach, Phys. Rev. B **93**, 144409 (2016).
23. A. Ghosh, K. Garello, C. O. Avci, M. Gabureac and P. Gambardella, Phys. Rev. Appl. **7**, 014004 (2017).
24. P. Chen, Y. Du, B. Yang, P. Lin, G. Guo, M. Pakala and C. Lai, Phys. Rev. Mater. **2**, 064408 (2018).
25. O. Mosendz, V. Vlaminck, J. E. Pearson, F. Y. Fradin, G. E. W. Bauer, S. D. Bader and A. Hoffmann, Phys. Rev. B **82**, 214403 (2010).
26. M. Morota, Y. Niimi, K. Ohnishi, D. H. Wei, T. Tanaka, H. Kontani, T. Kimura and Y. Otani, Phys. Rev. B **83**, 174405 (2011).
27. P. M. Haney, H. Lee, K. Lee, A. Manchon and M. D. Stiles, Phys. Rev. B **87**, 174411 (2013).
28. W. Wang, T. Wang, V. P. Amin, Y. Wang, A. Radhakrishnan, A. Davidson, S. R. Allen, T. J. Silva, H. Ohldag, D. Balzar, B. L. Zink, P. M. Haney, J. Q. Xiao, D. G. Cahill, V. O. Lorenz and X. Fan, Nat. Nanotech. **14**, 819 (2019).

This is the author's peer reviewed, accepted manuscript. However, the online version of record will be different from this version once it has been copyedited and typeset.

PLEASE CITE THIS ARTICLE AS DOI: 10.1063/5.0331050

29. S. Finizio, A. Kronenberg, M. Vafaei, M. Foerster, K. Litzius, A. de Lucia, T. O. Menteş, L. Aballe, B. Krüger, M. Jourdan and M. Kläui, *New J. Phys.* **17**, 083030 (2015).
30. J. Han, B. C. McGoldrick, C. Chou, T. S. Safi, J. T. Hou, L. Liu, *Appl. Phys. Lett.* **119**, 212409 (2021).
31. T. Tanaka, H. Kontani, M. Naito, T. Naito, D. S. Hirashima, K. Yamada, and J. Inoue, *Phys. Rev B* **77**, 165117 (2008).
32. D. Go, H. Lee, P. M. Oppeneer, S. Blügel, and Y. Mokrousov, *Phys. Rev B* **109**, 174435 (2024).

Fig.1

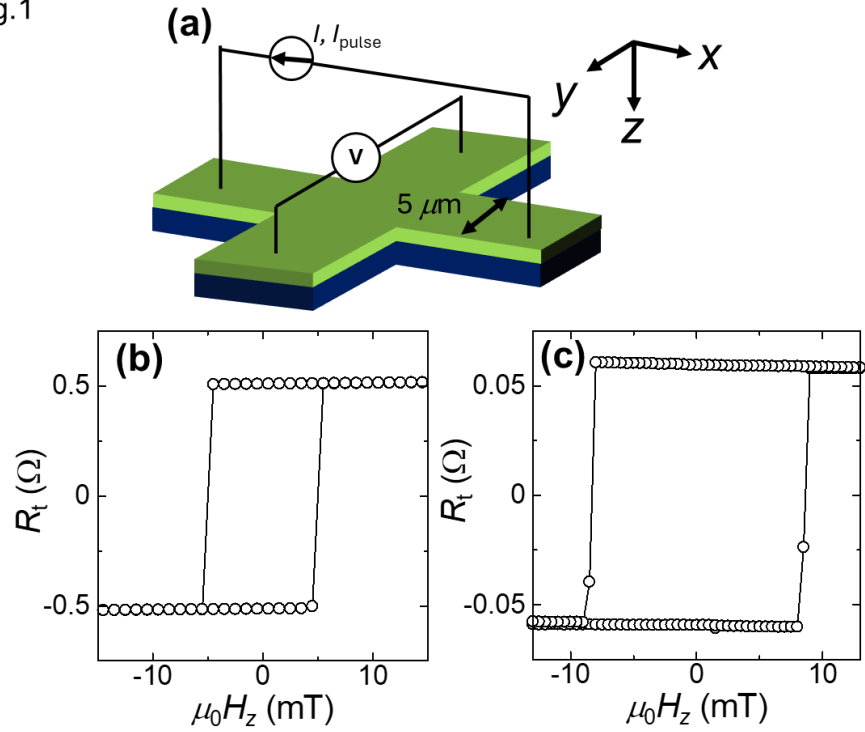


Fig. 1. (a) Schematic device structure and measurement setup with the definition of the Cartesian coordinate system used in this study. (b) and (c) Transverse resistance R_t as a function of out-of-plane magnetic field $\mu_0 H_z$ under $I = +100 \mu\text{A}$ at room temperature for Pd/CMG and Pd/CMS, respectively.

Fig.2

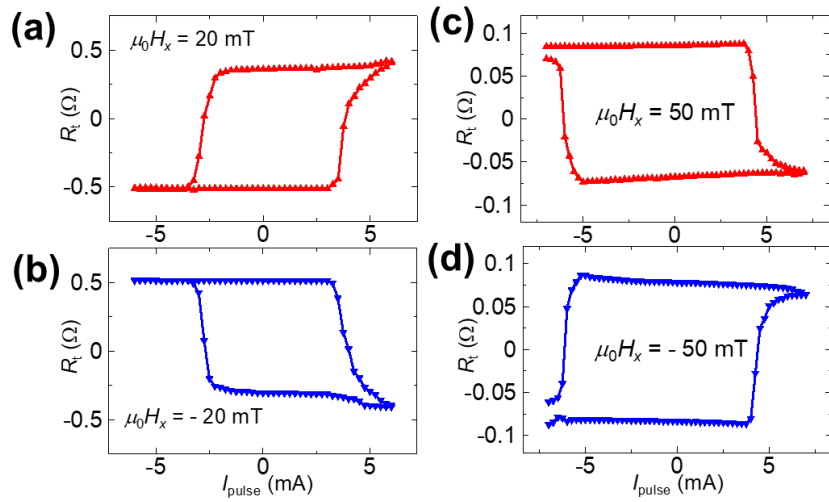


Fig. 2. (a) and (b) ((c) and (d)) R_t as a function of I_{pulse} for Pd/CMG (Pd/CMS) under $\mu_0 H_x = +20$ and -20 mT ($\mu_0 H_x = +50$ and -50 mT), respectively.

Fig.3

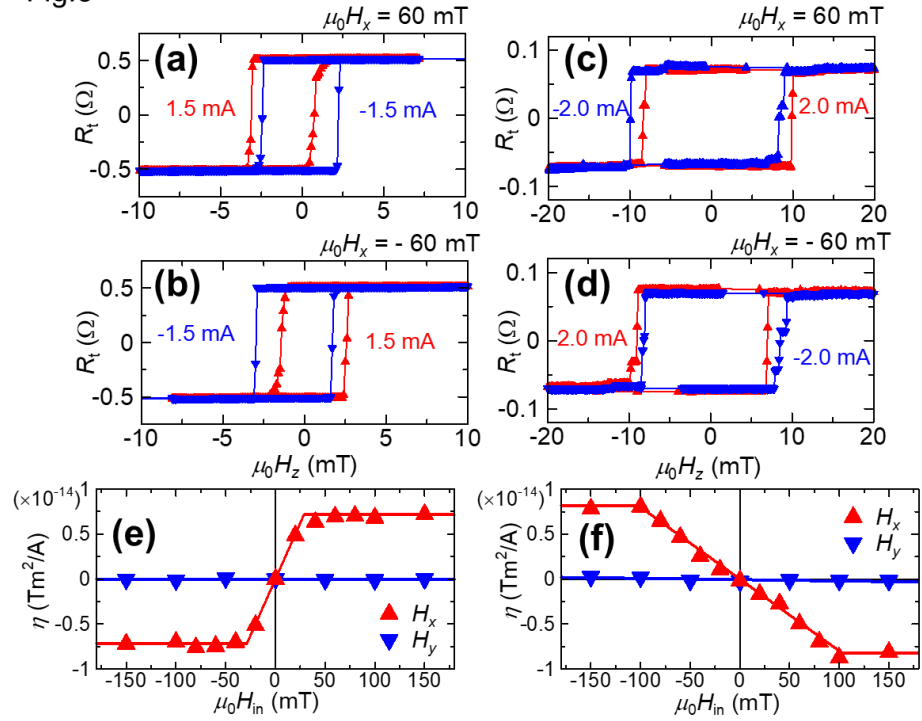


Fig. 3. (a) and (b) ((c) and (d)) R_t measured with $I = \pm 1.5$ (± 2.0) mA as a function of $\mu_0 H_z$ for Pd/CMG (Pd/CMS) under $\mu_0 H_x = -60$ and $+60$ mT, respectively. η as a function of $\mu_0 H_{in}$ ($\mu_0 H_x$ or $\mu_0 H_y$) for (e) Pd/CMG and (f) Pd/CMS. Red and blue triangles represent data obtained under $\mu_0 H_x$ and $\mu_0 H_y$, respectively.

Fig.4

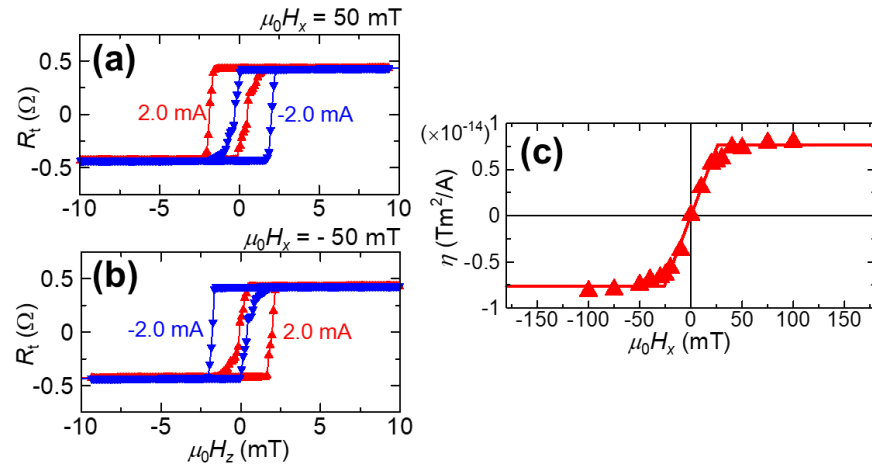


Fig. 4. (a) and (b) R_t measured with $I = \pm 2.0$ mA as a function of $\mu_0 H_z$, respectively, under $\mu_0 H_x = -50$ and $+50$ mT for the Pd/CMG [100]. (c) η as a function of $\mu_0 H_x$ for Pd/CMG [100].

Fig.5

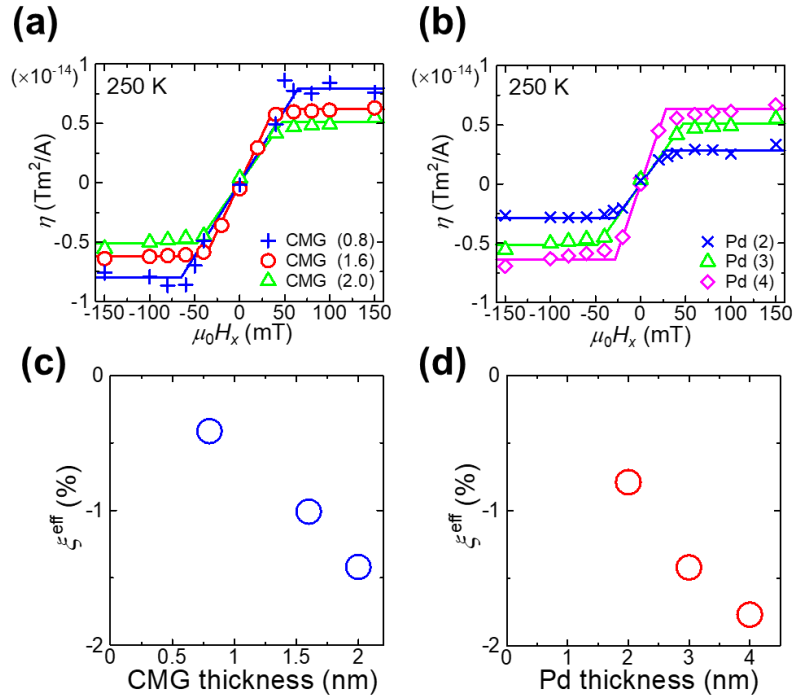


Fig. 5. (a) and (b) η as a function of $\mu_0 H_x$ at 250 K for Pd(3)/CMG(0.8, 1.6, and 2.0) and Pd(2, 3, and 4)/CMG(2.0), respectively. (c) and (d) ζ^{eff} as a function of CMG and Pd thicknesses for Pd/CMG, respectively.