

Supporting Information

Anomalous spin current anisotropy in a noncollinear antiferromagnet

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Note 1. Spin Hall conductivity tensors of noncollinear antiferromagnetic Mn₃Pt

Table S1 shows the tensors of time reversal-even ($\mathcal{T}$ -even) and time reversal-odd ($\mathcal{T}$ -odd) spin Hall conductivity (SHC) in noncollinear antiferromagnetic Mn₃X (X= Pt, Ir or Rh) for $\phi_E = 0^\circ$. For a finite ϕ_E , the coordinate system is transformed by a rotation matrix D , and the associated SHC tensors are then obtained as follows

$$\sigma_{(\phi_E)_{i,j}}^{s,k} = \sum_{l,m,n} D_{il} D_{jm} D_{kn} \sigma_{(\phi_E=0^\circ)_{lm}}^{s,n}.$$

For the SHC components associated with the out-of-plane spin current investigated in this work, we find the $\mathcal{T}$ -even SHC are dependent on the current direction as:

$$\begin{aligned} \sigma_{zx}^{x,\text{even}}(\phi_E) &= b \cos 2\phi_E, \\ \sigma_{zx}^{y,\text{even}}(\phi_E) &= -d + b \sin 2\phi_E, \\ \sigma_{zx}^{z,\text{even}}(\phi_E) &= a(\sin \phi_E - \cos \phi_E). \end{aligned} \quad (\text{S1})$$

Therefore, the magnitudes of the $\mathcal{T}$ -even SHC are the same for currents along the primary directions [100] ($\phi_E = 0^\circ$) and [010] ($\phi_E = 90^\circ$).

Similarly, we can obtain the ϕ_E dependence of $\mathcal{T}$ -odd SHC:

$$\begin{aligned} \sigma_{zx}^{x,\text{odd}}(\phi_E) &= B + D \sin 2\phi_E, \\ \sigma_{zx}^{y,\text{odd}}(\phi_E) &= D \cos 2\phi_E, \\ \sigma_{zx}^{z,\text{odd}}(\phi_E) &= A(\sin \phi_E + \cos \phi_E). \end{aligned} \quad (\text{S2})$$

These $\mathcal{T}$ -odd SHC for currents along the primary directions [100] ($\phi_E = 0^\circ$) and [010] ($\phi_E = 90^\circ$) also have the same magnitudes.

However, the net SHC σ_{zx}^p contributed by the intertwined $\mathcal{T}$ -even and $\mathcal{T}$ -odd spin Hall effect (SHE) has a more complicated anisotropy in Mn₃X, as shown in Eq. (3) in the main text. We schematically plot the angular dependence of σ_{zx}^p , $\sigma_{zx}^{p,\text{odd}}$, $\sigma_{zx}^{p,\text{even}}$ in Fig. 1e by assuming the $\mathcal{T}$ -odd SHE is stronger than $\mathcal{T}$ -even SHE using the parameters of $A = 1$, $B = 0.5$, $D = 1$, and $a = 0.5$, $b = 0.5$, $d = -0.5$.

Table S1: The tensors for $\mathcal{T}$ -even and $\mathcal{T}$ -odd SHC in noncollinear antiferromagnetic Mn_3X .

$\phi_{\text{E}} = 0^\circ$ $(x \parallel [\mathbf{100}],$ $y \parallel [\mathbf{010}],$ $z \parallel [\mathbf{001}])$	σ^x $= \begin{bmatrix} \sigma_{xx}^x & \sigma_{xy}^x & \sigma_{xz}^x \\ \sigma_{yx}^x & \sigma_{yy}^x & \sigma_{yz}^x \\ \sigma_{zx}^x & \sigma_{zy}^x & \sigma_{zz}^x \end{bmatrix}$	σ^y $= \begin{bmatrix} \sigma_{xx}^y & \sigma_{xy}^y & \sigma_{xz}^y \\ \sigma_{yx}^y & \sigma_{yy}^y & \sigma_{yz}^y \\ \sigma_{zx}^y & \sigma_{zy}^y & \sigma_{zz}^y \end{bmatrix}$	σ^z $= \begin{bmatrix} \sigma_{xx}^z & \sigma_{xy}^z & \sigma_{xz}^z \\ \sigma_{yx}^z & \sigma_{yy}^z & \sigma_{yz}^z \\ \sigma_{zx}^z & \sigma_{zy}^z & \sigma_{zz}^z \end{bmatrix}$
$\mathcal{T}$ -odd	$\begin{bmatrix} E & A & A \\ B & C & D \\ B & D & C \end{bmatrix}$	$\begin{bmatrix} C & B & D \\ A & E & A \\ D & B & C \end{bmatrix}$	$\begin{bmatrix} C & D & B \\ D & C & B \\ A & A & E \end{bmatrix}$
$\mathcal{T}$ -even	$\begin{bmatrix} 0 & -a & a \\ b & -c & -d \\ -b & d & c \end{bmatrix}$	$\begin{bmatrix} c & -b & D \\ a & 0 & -a \\ -d & b & -c \end{bmatrix}$	$\begin{bmatrix} -c & -d & b \\ d & c & -b \\ -a & a & 0 \end{bmatrix}$

Note 2. Characterization of the Mn₃Pt thin film

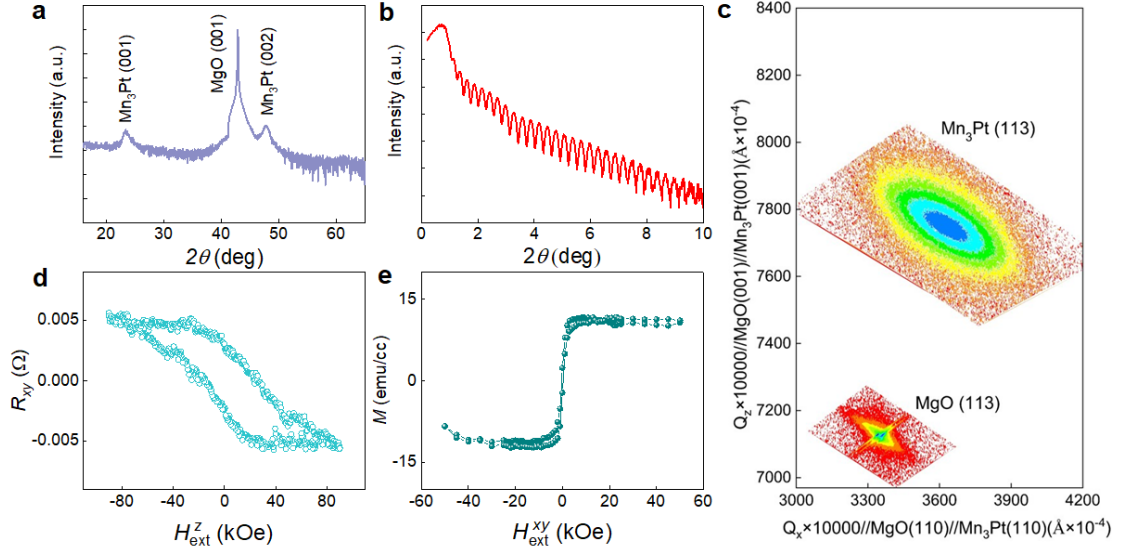


Fig. S1 Crystal structure characterization and the magnetic property of Mn₃Pt. **a** The X-ray diffraction θ - 2θ scan pattern of a Mn₃Pt(12 nm) film deposited on the MgO(001) substrate. **b** The X-ray reflectivity spectrum. **c**, Reciprocal space mapping around the (113) reflection. **d** The Hall resistance R_{xy} versus the out-of-plane magnetic field H_{ext}^z . **e** The in-plane magnetic hysteresis loop measured at room temperature.

The crystalline quality of the Mn₃Pt film was checked by using the X-ray diffraction technique. A representative θ - 2θ pattern is shown in Fig. S1a. Except for the (001) diffraction peak from the MgO substrate, the presence of peaks in the (001) family from Mn₃Pt illustrates the high degree of (001) texture. Figure S1b shows the X-ray reflectivity spectrum of an as-grown MgO(001)/Mn₃Pt heterostructure. Multiple oscillations can be seen up to a high 2θ angle, indicating a smooth and uniform film surface. Figure S1c shows the typical reciprocal space mapping pattern of the (113) plane. The presence of only the (113) peak is consistent with the characteristic of the Mn₃Pt crystal structure, which indicates that Mn₃Pt film grew epitaxially on the MgO substrate. Figure S1d shows the Hall resistance (R_{xy}) as a function of the out-of-plane magnetic field (H_{ext}^z) of the MgO(001)/Mn₃Pt heterostructure at room temperature. The obvious anomalous Hall effect confirms the noncollinear AFM nature of Mn₃Pt. The in-plane magnetic hysteresis loop was measured using a magnetic property measurement

system (MPMS, Quantum Design) with a 50 kOe in-plane magnetic field applied, as shown in Fig. S1e. The saturation magnetization $M_s \sim 10 \text{ emu/cm}^3$ can be obtained after subtracting the background signal, comparable to the reported value².

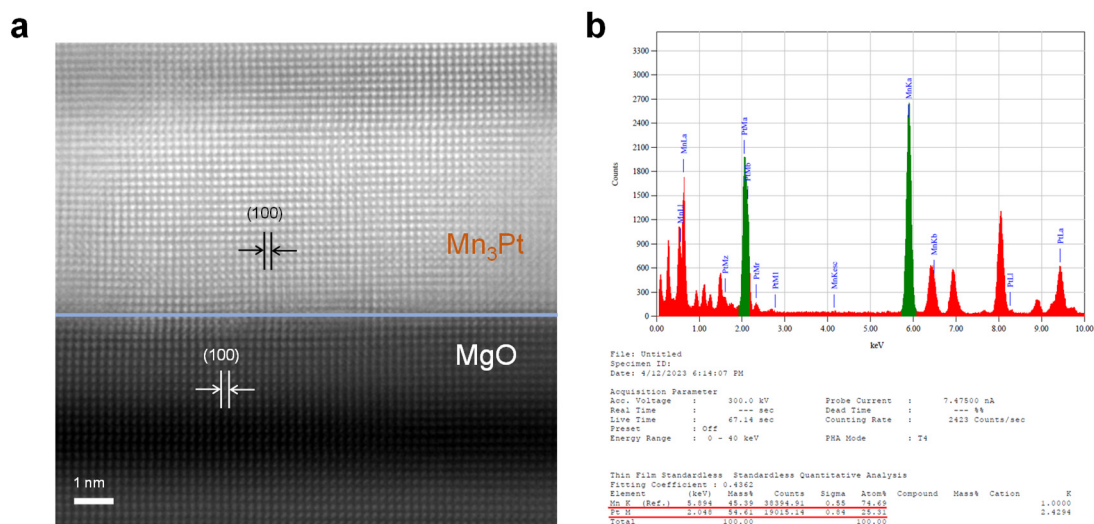


Fig. S2 Epitaxial structure characterization and atomic ratio of Mn₃Pt. **a** The cross-sectional transmission electron microscopy image and **b** the atomic ratio measured by EDS of a Mn₃Pt(12 nm) film deposited on the MgO(001) substrate.

The cross-sectional crystalline structure of the Mn₃Pt layer on the MgO (001) substrate imaged by aberration-corrected scanning transmission electron microscopy (AC-STEM, FEI Titan Themis 200) operated at 200 kV is shown in Fig. S2a. Good epitaxial growth of the Mn₃Pt thin film with a sharp interface to the MgO substrate can be observed. A Mn₃Pt unit cell along the [100] direction matches well with a MgO unit cell along the [100] direction. Furthermore, the atomic ratio of our sample has been checked by energy-dispersive X-ray spectroscopy (EDS). As shown in Fig. S2b, the atomic ratio is determined to be Mn : Pt = 74.69 : 25.31 $\approx$ 3 : 1.

Note 3. Spin-torque ferromagnetic resonance (ST-FMR) measurements in the Mn₃Pt/Py and Pt/Py bilayers

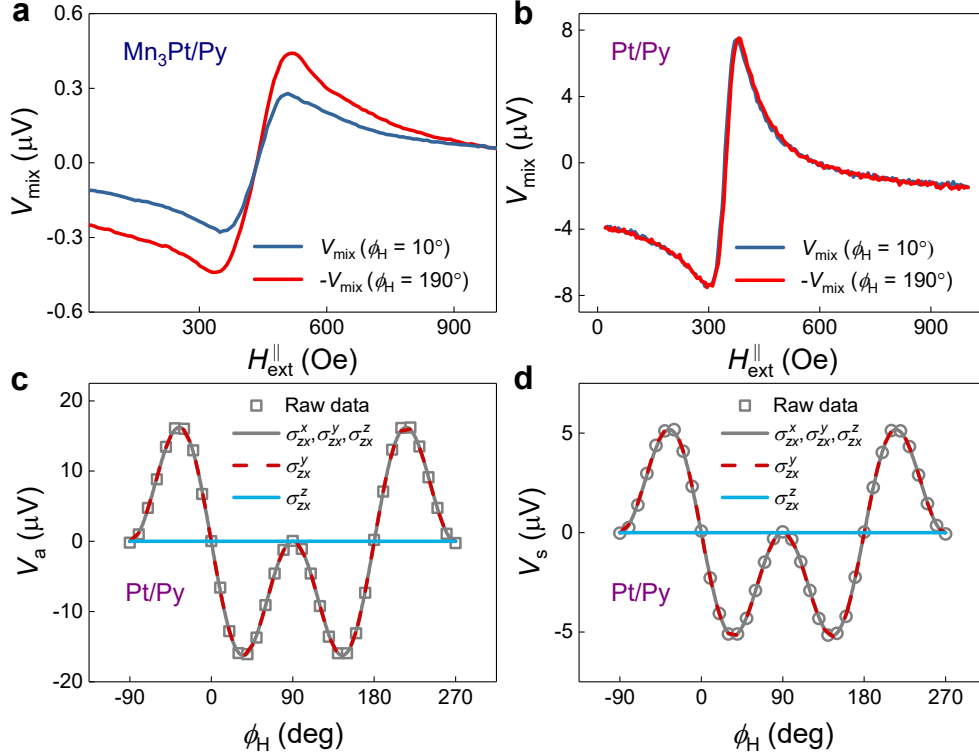


Fig. S3 The ST-FMR signals of the Mn₃Pt/Py and Pt/Py samples. Typical ST-FMR signal of the (a) Mn₃Pt(12 nm)/Py (13 nm) and (b) Pt(6 nm)/Py(6 nm) samples, with the magnetization oriented at 10° (blue line) and 190° (red line) relative to the current direction. **c** The antisymmetric component V_a (hollow squares for the raw data and the grey line for fitting) of Pt/Py bilayer as a function of the angle between the magnetic field and current ϕ_H and its decomposition into contributions from the spin polarizations σ_{ij}^p , where i , j , and p are the generated spin-current, the driven charge-current, and spin polarization directions, respectively. **d** Similar to (c) for the symmetric component V_s .

In the ST-FMR measurements, the magnetic moments in Py are set into precession by the SOT associated with the spin current generated in Mn₃Pt. Combined with the anisotropic magnetoresistance of Py, the output signal is a rectified voltage V_{mix} , whose lineshape can be decomposed into a symmetric component V_s and an antisymmetric component V_a near the resonant condition³⁻⁵:

$$V_{\text{mix}} = V_s \frac{\Delta H^2}{\Delta H^2 + (H_{\text{ext}}^{\parallel} - H_0)^2} + V_a \frac{\Delta H (H_{\text{ext}}^{\parallel} - H_0)}{\Delta H^2 + (H_{\text{ext}}^{\parallel} - H_0)^2}, \quad (\text{S3})$$

where H_0 is the resonant field, and ΔH is the linewidth of the resonant peak. The

components V_s and V_a characterize the in-plane SOT $\tau_{\parallel}$ and out-of-plane SOT $\tau_{\perp}$, respectively, allowing the full determination of the damping-like SOT $\mathbf{m} \times (\mathbf{m} \times \mathbf{p})$ and the field-like SOT $\mathbf{m} \times \mathbf{p}$ from all possible spin polarizations p ($p = x, y, z$)^{6,7}. Note that considering the in-plane $\mathbf{m}$ of Py, $\tau_{\perp}$ may come from the damping-like SOT associated with σ_{zx}^z , while it also includes the field-like contribution from σ_{zx}^y , σ_{zx}^x , and the Oersted field.

Figure S3a shows the representative ST-FMR spectra for the Mn₃Pt/Py bilayer which measured at 7 GHz with $\phi_H = 10^\circ$ and 190° , respectively, which does accord with the ST-FMR signals obtained at negative and positive magnetic fields. Here, ϕ_H is the angle between the microwave current I_{rf} and the magnetic field $H_{ext}^{\parallel}$. The observation of the ST-FMR signals V_{mix} does not exhibit a perfect inversion with the reversal of $H_{ext}^{\parallel}$, i.e., $V_{mix}(\phi_H = 10^\circ)$ and $-V_{mix}(\phi_H = 190^\circ)$ do not overlap, providing strong evidence of the presence of an unconventional SOT derived from spin polarizations other than σ_{zx}^y ^{2,8-13}.

In a typical heavy metal/ferromagnet bilayer with no broken crystal or magnetic structure symmetry like Pt/Py, the current-induced spin torque mainly comes from the Oersted field, the SHE, and/or the Rashba-Edelstein effect, which all exhibit a $\cos \phi_H \sin 2\phi_H$ dependence³. Different from the case for Mn₃Pt/Py bilayer, as shown in Fig. S3b, the ST-FMR signals V_{mix} for the Pt/Py bilayer exhibit a perfect inversion with the reversal of $H_{ext}^{\parallel}$. This is indeed the case for Pt/Py, as shown in Figs. S3c and 3d, pointing to no extra contribution except for σ_{zx}^y from the conventional SHE and confirming the reliability of our ST-FMR measurements.

Note 4. ST-FMR measurements in the Mn₃Pt/Py bilayer

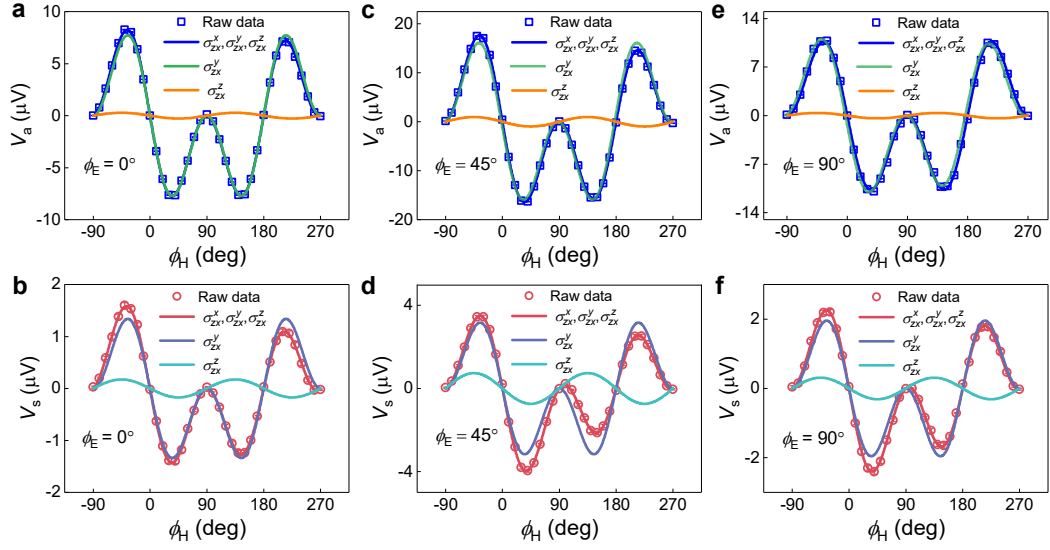


Fig. S4 Characterization of the SOT associated with σ_{ij}^p ($p = x, y, z$) by ST-FMR in Mn₃Pt/Py. a-f The ϕ_H dependence of V_a and V_s at selected ϕ_E of 0° , 45° , and 90° , here ϕ_E is the angle between the microwave current and the $[100]$ direction of Mn₃Pt. Their decomposition into contributions from the spin polarizations σ_{ij}^p can be derived from fittings (solid lines) to Eqs. (4) and (5) in the main text.

To examine the torque components quantitatively, the ST-FMR measurements as a function of the in-plane magnetic field angle ϕ_H were performed. Figures S4a-4f shows the ϕ_H dependence of V_a and V_s at selected ϕ_E of 0° , 45° , and 90° , where V_a and V_s can be well fitted by adding additional, unconventional torque terms through Eqs. (4) and (5) in the main text, respectively. These results give a strong evident, apart from σ_{zx}^y , that the presence of nonzero σ_{zx}^x and σ_{zx}^z in Mn₃Pt/Pt bilayer. Moreover, the σ_{zx}^z contribution is enhanced for $\phi_E = 45^\circ$ by comparing with $\phi_E = 0^\circ$, which is consistent with the previous observation of a stronger (weaker) σ_{zx}^z for current I applied parallel (perpendicular) to the magnetic mirror plane of Mn₃Pt². More importantly, an obvious discrepancy can be found between the cases of $\phi_E = 0^\circ$ and $\phi_E = 90^\circ$, which is unexpected considering their equivalency in both the crystal and magnetic structures, especially for high symmetry (001) plane of the spin source material with cubic structure.

Note 5. Calculation of the contribution from the Oersted field to the field-like-torque A_{FL}^y

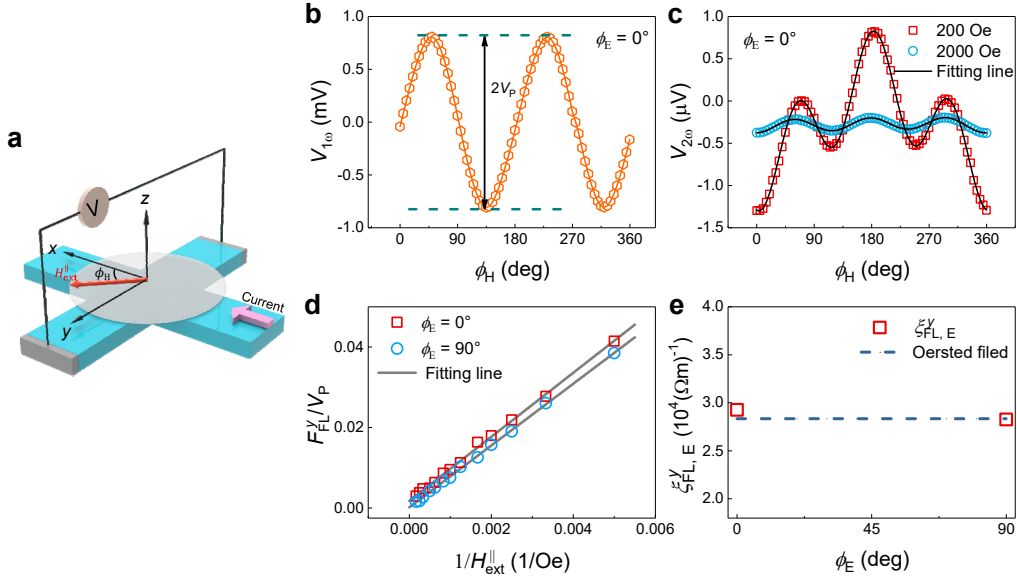


Fig. S5 **a** Geometry of the harmonic Hall measurements with rotating magnetic field in the xy plane $H_{\text{ext}}^{\parallel}$. **b** Typical first harmonic Hall voltage as a function of ϕ_H under $H_{\text{ext}}^{\parallel} = 200$ Oe and an a.c. current along the $[100]$ direction ($\phi_E = 0^\circ$). **c** Typical second harmonic Hall voltage as a function of ϕ_H for an a.c. current along the $[100]$ direction ($\phi_E = 0^\circ$) for two different magnitudes of magnetic field. **d** Normalized second harmonic Hall voltages for $\phi_E = 0^\circ$ and 90° as a function of the inverse of the applied magnetic field. **e** Symbols: measured values of $\xi_{\text{FL},E}^y$ from the second harmonic Hall measurements. Dashed line: estimated contribution from the Oersted field.

According to the previous work¹³, we can use the value of field-like-torque A_{FL}^y generated by σ_{zx}^y as a measure of the current density in the heavy metal to quantify the amplitude of the damping-like torque efficiencies per unit current density only if the Oersted field is the dominant source for A_{FL}^y . Therefore, in order to investigate whether the Oersted field is the dominant source for A_{FL}^y in our samples, we should calculate the A_{FL}^y by second harmonic Hall measurement.

A sinusoidal a.c. current with a frequency of 13.7 Hz was applied in a Hall bar device with $\phi_E = 0^\circ$ and 90° , and the first and second harmonic Hall voltages were

simultaneously measured by two lock-in amplifiers. An in-plane magnetic field $H_{\text{ext}}^{\parallel}$ was applied at various angles ϕ_H relative to the current direction, as shown in Fig. S5a. The a.c. current through the Mn_3Pt layer produces both periodic in-plane and out-of-plane torques on the magnetization of the Py layer, causing magnetization oscillation around the equilibrium direction that changes both the anomalous Hall resistance and the planar Hall resistance¹⁴. The first ($V_{1\omega}$) and second harmonic Hall voltage $V_{2\omega}$, is then¹⁴⁻¹⁷:

$$V_{1\omega} = V_P \sin 2\phi_H \sin^2 \theta + V_A \cos \theta, \quad (\text{S4})$$

$$V_{2\omega} = D_{\text{DL}}^y \cos \phi_H + D_{\text{DL}}^x \sin \phi_H + D_{\text{DL}}^z \cos 2\phi_H + F_{\text{FL}}^y \cos \phi_H \cos 2\phi_H + F_{\text{FL}}^x \sin \phi_H \cos 2\phi_H + F_{\text{FL}}^z, \quad (\text{S5})$$

with

$$D_{\text{DL}}^y = -\frac{\tau_{\text{DL}}^y}{\gamma} \frac{V_A}{2(H_{\text{ext}}^{\parallel} + H_k)} + V_{\text{ANE}} + V_{\text{ONE}} H_{\text{ext}}^{\parallel}, \quad (\text{S6})$$

$$D_{\text{DL}}^x = -\frac{\tau_{\text{DL}}^x}{\gamma} \frac{V_A}{2(H_{\text{ext}}^{\parallel} + H_k)}, \quad (\text{S7})$$

$$D_{\text{DL}}^z = -\frac{\tau_{\text{DL}}^z}{\gamma} \frac{V_P}{H_{\text{ext}}^{\parallel}}, \quad (\text{S8})$$

$$F_{\text{FL}}^y = -H_{\text{FL}}^y \frac{V_P}{H_{\text{ext}}^{\parallel}}, \quad (\text{S9})$$

$$F_{\text{FL}}^x = -H_{\text{FL}}^x \frac{V_P}{H_{\text{ext}}^{\parallel}}, \quad (\text{S10})$$

$$F_{\text{FL}}^z = H_{\text{FL}}^z \frac{V_A}{2(H_{\text{ext}}^{\parallel} + H_k)} + C, \quad (\text{S11})$$

where D_{DL}^p and F_{DL}^p are coefficients for the damping-like and field-like SOT generated by σ_{zx}^p , respectively. τ_{DL}^p and H_{FL}^p are the damping-like torques and the effective fields associated with the field-like torque generated by σ_{zx}^p , respectively. Note that the in-plane Oersted field as well as the spin-transfer torque can contribute to H_{FL}^y . θ and ϕ_H are the polar and azimuthal angles of the magnetization vector, respectively. V_P is the coefficient of the planar Hall voltage, $V_{\text{PHE}} = V_P \sin 2\phi_H$, for a given direction the alternating current, and V_A is the coefficient of the anomalous Hall voltage $V_{\text{AHE}} = V_A \cos \theta$. Note that the contribution of V_{AHE} to $V_{1\omega}$ is negligible since the Py layer exhibits an in-plane anisotropy. V_{ANE} is an anomalous

Nernst voltage. $V_{\text{ONE}}H_{\text{ext}}^{\parallel}$ is a voltage due to the ordinary Nernst effect. H_k characterizes the out-of-plane magnetic anisotropy (positive for samples with an in-plane anisotropy), and C accounts for a constant background. The field-like torque efficiencies per unit electric field associated with each component p are

$$\xi_{\text{FL,E}}^p = \frac{2e}{\hbar} M_s t_{\text{FM}} \frac{\mu_0 H_{\text{FL}}^p}{E}, \quad (\text{S12})$$

where E is the peak electric field associated with the a.c. current.

We show the ϕ_H dependence for the harmonic Hall voltages of the Mn₃Pt(12 nm)/Py(13 nm) sample in Fig. S5b-5c for an a.c. current applied in the [100] direction ($\phi_E = 0^\circ$). In Fig. S5c, we show the second harmonic Hall voltage as a function of ϕ_H under an 200 Oe (red) and 2000 Oe (blue) magnetic field. The corresponding fitting lines based on Eq. (S5) are shown in black lines. To quantify the effective fields for the out-of-plane torque terms, F_{FL}^y is normalized with respect to V_p , plotted as a function of $1/H_{\text{ext}}^{\parallel}$ which is fitted to straight lines for $\phi_E = 0^\circ$, as shown in Fig. S5d. From the slopes of the fitting lines and Eq. (S12), we calculate the field-like torque efficiencies $\xi_{\text{FL,E}}^y$ and show the corresponding results for $\phi_E = 0^\circ$ and 90° in Fig. S5e. It is found that $\xi_{\text{FL,E}}^y$ shows little variation with ϕ_E . Meanwhile, the current-induced Oersted field is $H_{\text{Oe}} = \frac{1}{2} j_{\text{HM}} t_{\text{HM}}$, where j_{HM} and t_{HM} are the current density and thickness of the Mn₃Pt layer, and the Oersted field translates into a torque efficiency as following:

$$\xi_{\text{Oersted,E}}^y = \frac{2e}{\hbar} \frac{\mu_0 M_s t_{\text{FM}} t_{\text{HM}}}{2\rho_{xx}}, \quad (\text{S13})$$

where ρ_{xx} is the resistivity of the Mn₃Pt layer. Substituting in corresponding values of our samples, $\mu_0 M_s = 0.79$ T, $t_{\text{FM}} = 13$ nm, $t_{\text{HM}} = 12$ nm, and $\rho_{xx} = 176 \mu\Omega\text{cm}$ ¹⁸ yields the blue dashed line in Fig. S5e, in good agreement with the data points. The Oersted torque is seen to contribute at least 96% of the field-like torque efficiency $\xi_{\text{FL,E}}^y$ regardless of the electric-field angle ϕ_E , indicating A_{FL}^y is dominated by the Oersted field, making A_{FL}^y a good measure of the current density in the Mn₃Pt layer. A similar

approach was applied in a previous study of RuO₂/Py bilayer¹³.

Note 6. The exchange bias effect of Mn₃Pt based heterostructures

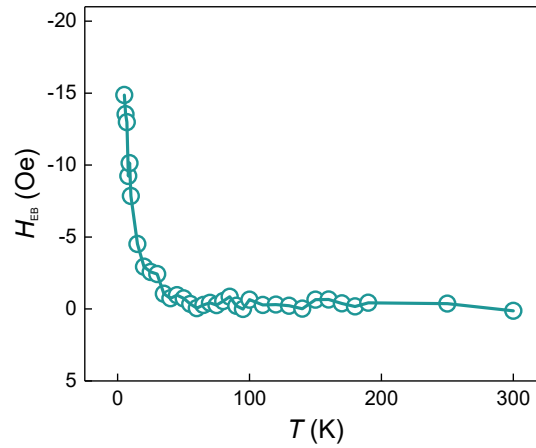


Fig. S6 The temperature dependence of the exchange bias field of the Mn₃Pt/Ti/CoFeB/MgO/SiO₂ heterostructure extracted from the AHE curves.

To determine the influence of the exchange bias on the field-free magnetization switching of the Mn₃Pt/Ti/CoFeB/MgO/SiO₂ heterostructure, we measured the AHE curves in the temperature range of 5-300 K. The values of the exchange bias field H_{EB} extracted from AHE curves at different temperatures are shown in Fig. S6. No exchange bias effect was observed in the wide temperature range of 100 to 300 K, which can be attributed to the thick Ti layer which effectively decouples the antiferromagnetic Mn₃Pt and ferromagnetic CoFeB layer. The exchange bias effect was only observed at sufficiently low temperatures (below ~50 K) with enhanced exchange coupling. This result unambiguously excludes the exchange bias as the possible reason for the field-free switching behavior of Mn₃Pt/Ti/CoFeB/MgO/SiO₂ heterostructure at room temperature.

Note 7. The anomalous Hall effect at different ϕ_E

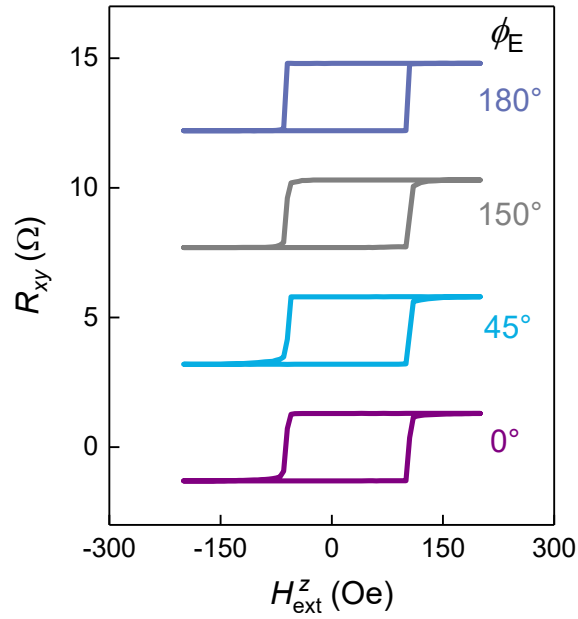


Fig. S7 The anomalous Hall resistance R_{xy} as a function of the out-of-plane magnetic field H_{ext}^z at different ϕ_E (0° , 45° , 150° and 180°).

As shown in Fig. S7, the anomalous Hall effect (AHE) curves of $\text{Mn}_3\text{Pt}/\text{Ti}/\text{CoFeB}/\text{MgO}/\text{SiO}_2$ heterostructure at different ϕ_E (0° , 45° , 150° , and 180°) were measured under the magnetic field along the z axis. According to the square shape of the out-of-plane hysteresis, we identified the good perpendicular magnetic anisotropy of the sample.

Note 8. The AHE loop shift of the $\text{Mn}_3\text{Pt}/\text{Ti}/\text{CoFeB}/\text{MgO}/\text{SiO}_2$ heterostructure with $\phi_E = 45^\circ$

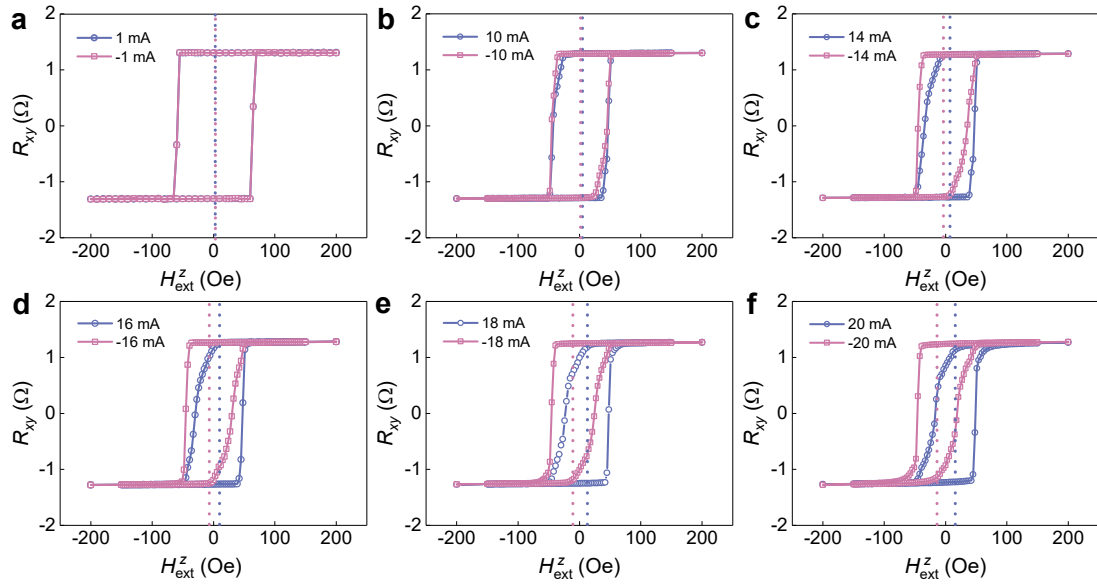


Fig. S8 The anomalous Hall loops under different pulsed d.c. currents for the Hall bar device with $\phi_E = 45^\circ$.

Figure S8 shows the evolution of the AHE loop shift with increasing the pulsed d.c. current in the $\text{Mn}_3\text{Pt}/\text{Ti}/\text{CoFeB}/\text{MgO}/\text{SiO}_2$ heterostructure for Hall bar device with $\phi_E = 45^\circ$. As shown in Figs. S8a and 8b, there is no shift observed when the current amplitude is below 10 mA. While above 10 mA, in Figs. S8c-8f, AHE loop shift occurs and increases almost linearly with the increase of I , indicating the existence of H_{eff}^z .

Note 9. The AHE loops in the $\text{Mn}_3\text{Pt}/\text{Ti}/\text{CoFeB}/\text{MgO}/\text{SiO}_2$ heterostructure under $I = \pm 20$ mA for different ϕ_E

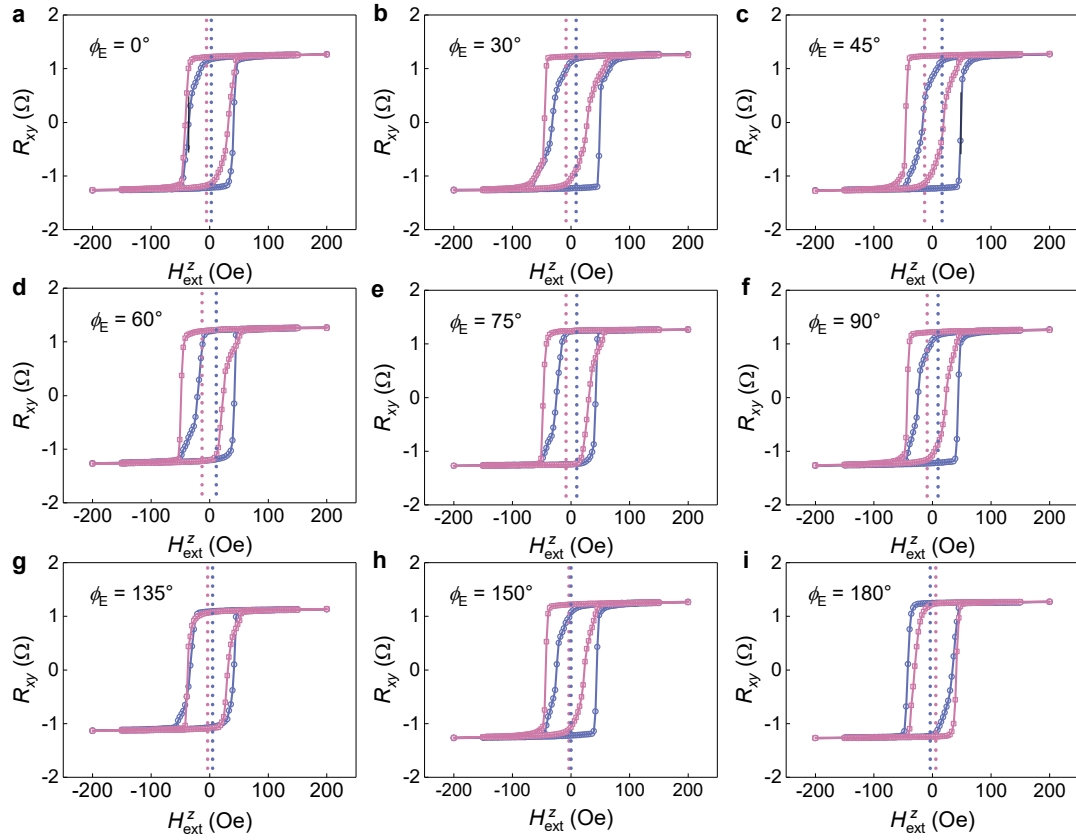


Fig. S9 AHE loops under a pulsed d.c. current $I = \pm 20$ mA for varying ϕ_E .

Figure S9 shows the AHE loops of the $\text{Mn}_3\text{Pt}/\text{Ti}/\text{CoFeB}/\text{MgO}/\text{SiO}_2$ heterostructure measured by applying a d.c. current $I = \pm 20$ mA for different ϕ_E ranging from 0° to 180° . The values of the AHE loop shift vary with ϕ_E , indicating the anisotropy of H_{eff}^z which is induced by the anisotropy of σ_{zx}^z . The ϕ_E dependence of H_{eff}^z obtained is summarized in the main text (Fig. 3e).

Note 10. Evaluation of Joule heating effect

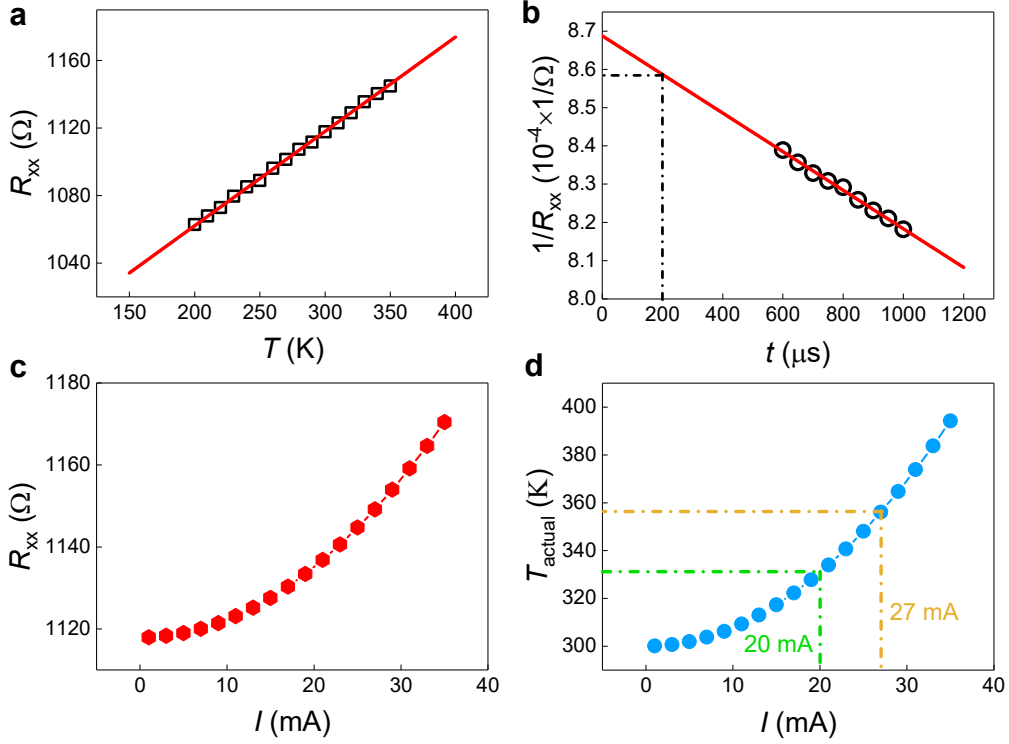


Fig. S10 **a** The resistance R_{xx} of the $Mn_3Pt(5)/Ti(3)/CoFeB(1)/MgO(2)/SiO_2(2)$ device as a function of the temperature. The red line is a linear fit. **b** The pulse width dependence of the conductance of the $Mn_3Pt(5)/Ti(3)/CoFeB(1)/MgO(2)/SiO_2(2)$ device. The red line is a linear fit. **c** The resistance of the $Mn_3Pt(5)/Ti(3)/CoFeB(1)/MgO(2)/SiO_2(2)$ device versus the pulse current amplitude. (Current pulse width = 200 μs). **d** The actual device temperature with different pulse amplitudes. (Current pulse width = 200 μs).

To determine the actual temperature of the device during the loop shift and magnetization switching measurements, we first measured the temperature dependence of the longitudinal resistance R_{xx} under a small DC current $I \sim 0.1$ mA. The actual temperature T of the device can be estimated by the change of R_{xx} based on the R_{xx} versus T curve in Fig. S10a.

Since the resistance R_{xx} of our $Mn_3Pt(5)/Ti(3)/CoFeB(1)/MgO(2)/SiO_2(2)$ device is in the range of k Ω , the measurement range of the voltage meter needs to be adjusted to 100 V during the measurement, and the pulse width is required to be larger than 600 μs in the resistance measurements. In contrast, we use a pulse width of 200 μs

in the loop shift and magnetization switching measurements. To compare the results in different measurements with different pulse widths, we plot R_{xx} as a function of the pulse width in Fig. S10b. The data is shown to follow the empirical formula $R_{xx} = \frac{\beta}{\alpha - I^2 \times t}$, where I and t are the pulse current magnitude and pulse width, respectively, and α and β are constant fitting parameters¹⁹. By extrapolating the linear fit of $1/R_{xx}$ to a pulse width of 200 μs , we can obtain the resistance R_{xx} with 200 μs pulse width. We plot R_{xx} versus I in Fig. S10c and estimate the actual temperature with each pulse current by converting R_{xx} into actual temperature as shown in Fig. S10d. Based on these measurements, we estimate the actual device temperature to be ~ 331 K for the maximum current in the AHE loop shift measurement (Fig. 3 of the manuscript) and ~ 356 K for the maximum current in the magnetization switching measurement (Figs. 4c and 4d of the manuscript), which are well below the T_N of Mn_3Pt (~ 475 K).

Note 11. Field-free current-induced magnetization switching at different ϕ_E

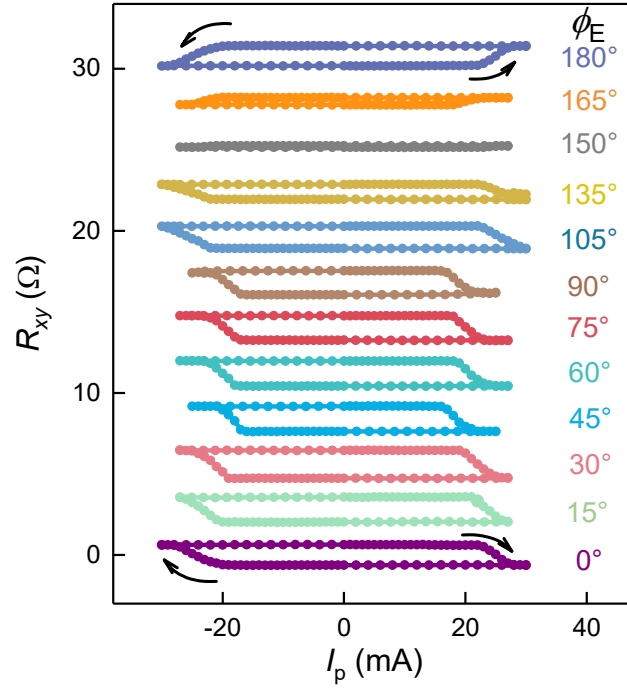


Fig. S11 Field-free current-induced magnetization switching of the $\text{Mn}_3\text{Pt}/\text{Ti}/\text{CoFeB}/\text{MgO}/\text{SiO}_2$ heterostructure for different ϕ_E .

Figure S11 shows the current-induced magnetization switching of the $\text{Mn}_3\text{Pt}/\text{Ti}/\text{CoFeB}/\text{MgO}/\text{SiO}_2$ heterostructure without the assistance of a magnetic field for ϕ_E ranging from 0° to 180° . As shown in Fig. S11, for the Hall bar with different ϕ_E , the switching ratio and switching polarity vary with ϕ_E . The field-free current-induced magnetization switching achieved illustrates the existence of σ_{zx}^z and its associated out-of-plane SOT in the $\text{Mn}_3\text{Pt}/\text{Ti}/\text{CoFeB}/\text{MgO}/\text{SiO}_2$ heterostructure. It is seen that the switching polarity for ϕ_E less than 150° is clockwise, whereas for ϕ_E from 150° to 180° it is anticlockwise. The behavior of the field-free current-induced magnetization switching for different ϕ_E can be attributed to the σ_{zx}^z induced spin torque, which is consistent with the trend of H_{eff}^z for different ϕ_E .

Note 12. The AHE loops in the $\text{Mn}_3\text{Pt}/\text{Ti}/\text{CoFeB}/\text{MgO}/\text{SiO}_2$ heterostructure for different premagnetization field

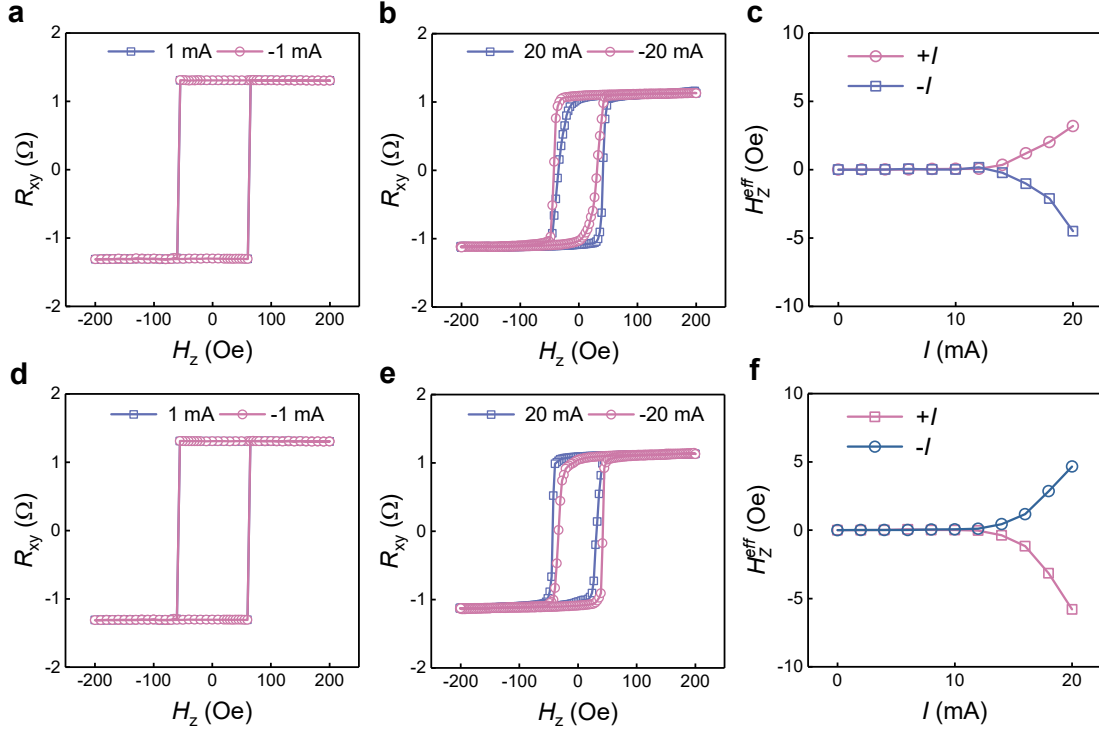


Fig. S12 a-c The AHE loops under $I = \pm 1$ mA, ± 20 mA, and the I dependence of H_Z^{eff} at selected $\phi_E = 0^\circ$ with a premagnetization field of 8 T along the [001] direction. **d-f** Similar to (a-c) but with a premagnetization field of 8 T along the [00 $\bar{1}$] direction.

Figure S12 shows the loop shift measurements for $\phi_E = 0^\circ$ with the application of a premagnetization field H_{pre} of 8 T along the [001] and [00 $\bar{1}$] direction. The expected polarity reversal is indeed observed between loop shift measurements with an H_{pre} of 8 T along the [001] and [00 $\bar{1}$] directions, consistent with the magnetization switching measurements and corroborates again the presence of the $\mathcal{T}$ -odd spin Hall effect, i.e., the magnetic spin Hall effect, and the presence of the nonvanishing net magnetization.

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