

Supplementary information for

Efficient conversion of orbital Hall current to spin current for spin-orbit torque switching

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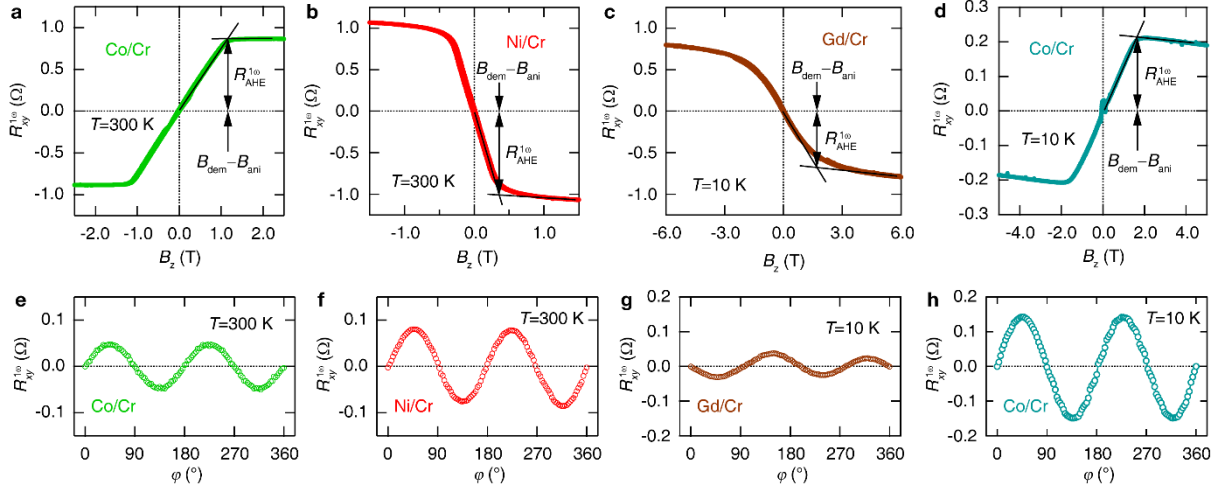
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Supplementary Note 1: Anomalous and planar Hall effect of FM/NM bilayers

In order to evaluate spin-orbit torques (SOTs) by in-plane harmonic Hall measurements (Eq. (2) in the main text), we measure both 1st harmonic anomalous Hall resistance ($R_{\text{AHE}}^{1\omega}$) and planar Hall resistance ($R_{\text{PHE}}^{1\omega}$). Supplementary Figures 1a-d present the 1st harmonic resistance ($R_{xy}^{1\omega}$) as a function of a perpendicular external magnetic field (B_z) of the FM (Co, Ni, and Gd)/Cr (7.5 nm) samples. From the results of Supplementary Figs. 1a-d, we extract $R_{\text{AHE}}^{1\omega}$, demagnetizing field (B_{dem}), and anisotropy field (B_{ani}). Note that the Co/Cr sample has a positive $R_{\text{AHE}}^{1\omega}$ while the Ni/Cr and Gd/Cr samples show the opposite sign [1-3]. Supplementary Figures 1e-h show azimuthal angle dependent 1st harmonic Hall resistance $R_{xy}^{1\omega}(\varphi)$ of the FM (Co, Ni, and Gd)/Cr (7.5 nm) samples, which is measured under a constant external magnetic field B_{ext} of 1 T. The $R_{\text{PHE}}^{1\omega}$ value is determined using $R_{xy}^{1\omega}(\varphi) = R_{\text{PHE}}^{1\omega} \sin 2\varphi$. Note that the sign of $R_{\text{PHE}}^{1\omega}$ for the Gd/Cr sample is negative, which may be due to negative anisotropic magnetoresistance of Gd [4]. We note that the $R_{\text{PHE}}^{1\omega}$ of the FM/Cr samples is independent of the magnitude of the external magnetic field.

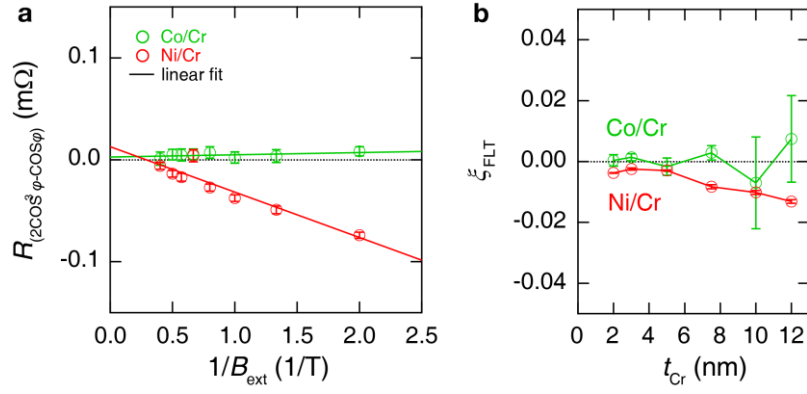


Supplementary Figure 1. Anomalous and planar Hall effects of FM/Cr samples. a-d, Anomalous Hall resistance of Co (3 nm)/Cr (7.5 nm) (a), Ni (2 nm)/Cr (7.5 nm) (b), Gd (10 nm)/Cr (7.5 nm) (c), and Co (10 nm)/Cr (7.5 nm) (d) samples. e-h, Planar Hall resistance of Co (3 nm)/Cr (7.5 nm) (e), Ni (2 nm)/Cr (7.5 nm) (f), Gd (10 nm)/Cr (7.5 nm) (g), and Co (10 nm)/Cr (7.5 nm) (h) samples. The measurements are conducted at 300 K [10 K] for Co (3 nm)/Cr and Ni (2 nm)/Cr [Gd (10 nm)/Cr and Co (10 nm)/Cr] samples.

Supplementary Note 2: Field-like spin-orbit torques of the FM/NM bilayers

Supplementary Figure 2a shows $(2\cos^3\varphi - \cos\varphi)$ component of $R_{xy}^{2\omega}(\varphi)$, $R_{(2\cos^3\varphi - \cos\varphi)}$, for Co/Cr, and Ni/Cr samples as a function of $1/B_{\text{ext}}$. The slope of $[R_{(2\cos^3\varphi - \cos\varphi)}/B_{\text{ext}}]$ represents $2R_{\text{PHE}}^{1\omega} \times (B_{\text{FLT}} + B_{\text{Oe}})$ of the sample (Eq. (2) in the main text). We find the $R_{(2\cos^3\varphi - \cos\varphi)}$ value of the Co (3 nm)/Cr (7.5 nm) sample is considerably smaller than that of the Ni (2 nm)/Cr (7.5 nm) sample. This indicates that the $(B_{\text{FLT}} + B_{\text{Oe}})$ value of the Co/Cr sample is much smaller than that of the Ni/Cr sample. Supplementary Figure 2b shows the estimated field-like torque efficiency, $\xi_{\text{FLT}} = (2e/\hbar)(M_S t_{\text{Co}} B_{\text{FLT}}/J_{\text{Cr}})$, where e is the electron charge, $\hbar$ is the reduced Planck constant, M_S is the saturation magnetization, t_{Co} is the Co thickness, and J_{Cr} is the current density flowing through Cr.

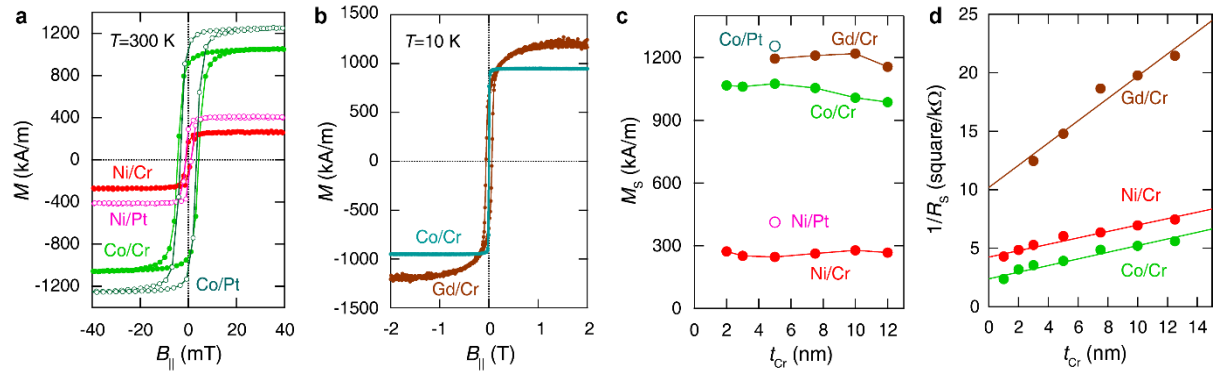
Note that the ξ_{FLT} in the Ni/Cr sample increases with Cr thickness, similar to the damping-like torque (DLT) shown in Fig. 1g of the main text. This similar behavior of field-like torque (FLT) and DLT suggests that they share the same origin, i.e. the orbital currents generated in the Cr layer. The FLT caused by orbital currents can be explained by a recent theoretical study [5]. It is found that when the spin (orbital) current generated in the Cr/FM bilayer is injected into an FM layer, the spin current relaxes quickly near the interface, but the orbital current transmits longer distances up to 30 atomic layers (~ 4.5 nm) of the FM layer. This results in the accumulation of orbital angular momentum at the other FM interface, which is converted into spin currents to generate FLT. Although additional studies are needed to prove it experimentally, these theoretical results show that FLT can be induced by orbital current due to its long diffusion length in the FM layer.



Supplementary Figure 2. Field-like torques of Co/Cr and Ni/Cr samples. **a**, $R_{(2\cos^3\varphi - \cos\varphi)}$ of Co (3 nm)/Cr (7.5 nm) and Ni (2 nm)/Cr (7.5 nm) samples versus $1/B_{\text{ext}}$. The solid lines represent the linear fits to the data. **b**, The field-like torque efficiency (ξ_{FLT}) as a function of Cr thickness (t_{Cr}).

Supplementary Note 3: Saturation magnetization and current shunting effect

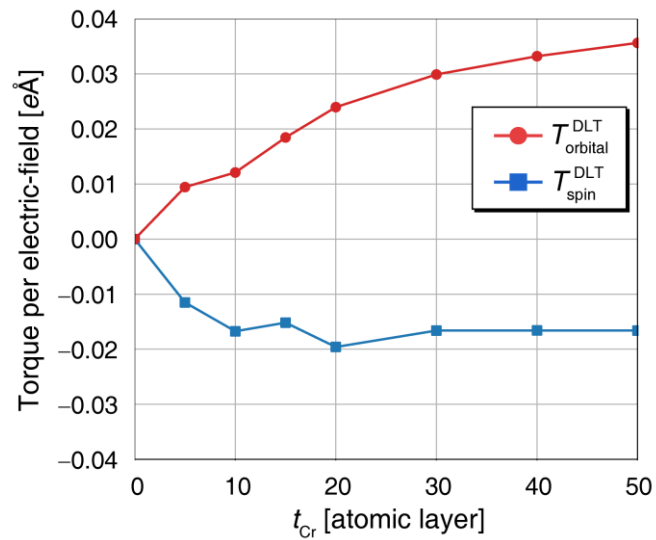
Supplementary Figures 3a,b show the magnetic hysteresis curves of various FM/NM bilayer samples measured by vibrating sample magnetometry. The saturation magnetization M_S values of the FM/NM samples are summarized in Supplementary Fig. 3c, demonstrating that the M_S values are not significantly varied with the Cr thickness (t_{Cr}). The M_S values are 1042 ± 15 kA/m for Co/Cr, 263 ± 5 kA/m for Ni/Cr, 1255 kA/m for Co/Pt, and 412 kA/m for Ni/Pt. Supplementary Figure 3d presents the inverse of the sheet resistance ($1/R_S$) for the Ni/Cr, Co/Cr, and Gd/Cr samples as a function of t_{Cr} . Using a linear fit of $1/R_S$ versus t_{Cr} , the Cr resistivity (ρ_{Cr}) is estimated; $364.19 \pm 30.24 \mu\Omega \cdot \text{cm}$ for Ni/Cr, $353.06 \pm 34.03 \mu\Omega \cdot \text{cm}$ for Co/Cr at 300K, and $105.13 \pm 10.42 \mu\Omega \cdot \text{cm}$ for Gd/Cr sample at 10K. The FM resistivity (ρ_{FM}) is extracted from the y-axis intercept; $\rho_{Ni} = 47.18 \mu\Omega \cdot \text{cm}$, $\rho_{Co} = 125.60 \mu\Omega \cdot \text{cm}$, and $\rho_{Gd} = 98.11 \mu\Omega \cdot \text{cm}$. The current density in the Cr layer (J_{Cr}) is calculated by $J_{Cr} = (I_0/t_{Cr}W)[t_{Cr}\rho_{FM}/(t_{FM}\rho_{Cr} + t_{Cr}\rho_{FM})]$, where I_0 is the root-mean-square amplitude of the AC current for the harmonic Hall measurement, $t_{Cr(FM)}$ is the Cr (FM) thickness, W is the width of a Hall-bar, and $\rho_{Cr(FM)}$ is the resistivity of Cr (FM).



Supplementary Figure 3. Saturated magnetization (M_S) and thickness dependent resistivity of FM/Cr samples. a,b, The hysteresis loops of Ni (2 nm)/Cr (7.5 nm), Co (3 nm)/Cr (7.5 nm), Ni (2 nm)/Pt (5 nm), Co (3 nm)/Pt (5 nm), **(a)**, Gd (10 nm)/Cr (7.5 nm), and Co (10 nm)/Cr (7.5 nm) **(b)** samples. The magnetic field is applied along the film plane ($B_{||}$) during measurement. **c,** The M_S of FM/NM samples as a function of t_{Cr} . **d,** The $1/R_S$ of FM/NM samples as a function of t_{Cr} . The solid lines represent the linear fits to the data.

Supplementary Note 4: Theoretical estimation of the orbital diffusion length in Cr

We calculate the spin torques generated by spin and orbital current in Cr/CoFe bilayer structures as a function of Cr thickness using first-principles calculations and spin continuity equations. Note that the calculation details are found in literature [5,6]. Supplementary Figure 4 presents the Cr thickness dependences of spin- and orbital-current-induced DLTs ($T_{\text{spin}}^{\text{DLT}}$ and $T_{\text{orbital}}^{\text{DLT}}$) under a constant electric field. Interestingly, the calculation results agree well with our experimental results (Fig. 1g in the main text); $T_{\text{spin}}^{\text{DLT}}$ saturates when $t_{\text{Cr}} \sim 20$ atomic layers (~ 3 nm), whereas the $T_{\text{orbital}}^{\text{DLT}}$ is not saturated at $t_{\text{Cr}} \sim 50$ atomic layers (~ 7 nm). This result supports that the thickness dependence of the ξ_{DLT} of the Cr/FM samples is due to the long orbital diffusion length.



Supplementary Figure 4. Spin torques induced by the spin ($T_{\text{spin}}^{\text{DLT}}$) and orbital ($T_{\text{orbital}}^{\text{DLT}}$) as a function of the Cr thickness (t_{Cr}) in a Cr/CoFe sample. The thickness of the CoFe layer is 20 atomic layers.

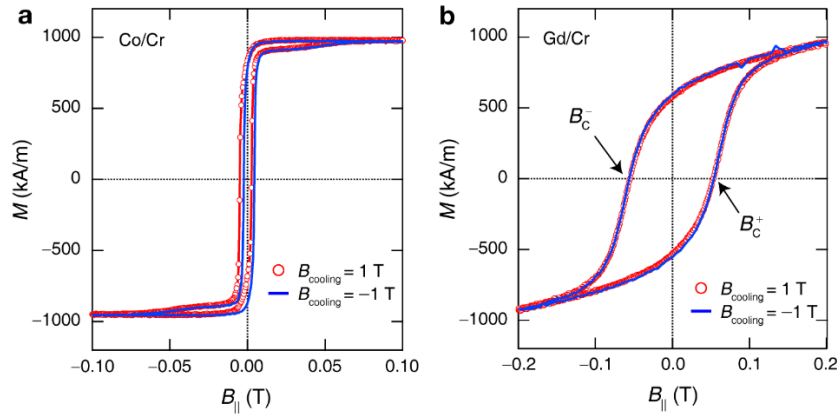
Supplementary Note 5: Effect of antiferromagnetic order of Cr at a low temperature

The bcc-Cr is known as a spin-density wave antiferromagnet (AFM) [7] and thus can exchange couple with an adjacent ferromagnet (FM) [8]. In order to clarify the effect of the Cr's AFM order on spin-orbit torque (SOT) measurements, we first examine the magnetic hysteresis loops of the Co (10 nm)/Cr (7.5 nm) and Gd (10 nm)/Cr (7.5 nm) films measured at 10 K using vibrating sample magnetometer. Supplementary Figure 5a shows the hysteresis loops of the Co/Cr sample, which were measured after cooling under in-plane magnetic fields ($B_{\text{cooling}} = \pm 1$ T). The hysteresis loop of the Co/Cr sample is shifted in the opposite direction to the applied magnetic field, indicating the exchange coupling developed between the Cr and Co layers. The exchange bias field B_{EB} , defined as $[B_C^+ + B_C^-]/2$, is ~ 1 mT for the Co/Cr sample. Here, $B_C^\pm$ is the positive or negative coercive field. This result clearly demonstrates the AFM nature of Cr at 10 K. On the other hand, the hysteresis loops of the Gd/Cr sample are the same regardless of the direction of the B_{cooling} (Supplementary Fig. 5b), indicating that no exchange interaction occurs between the Cr and Gd layers. Further study is required to understand why exchange coupling is absent in the Gd/Cr sample, but this allows us to rule out the effect of the AFM order on the harmonic Hall measurement results in the Gd/Cr sample (Fig. 2b of the main text).

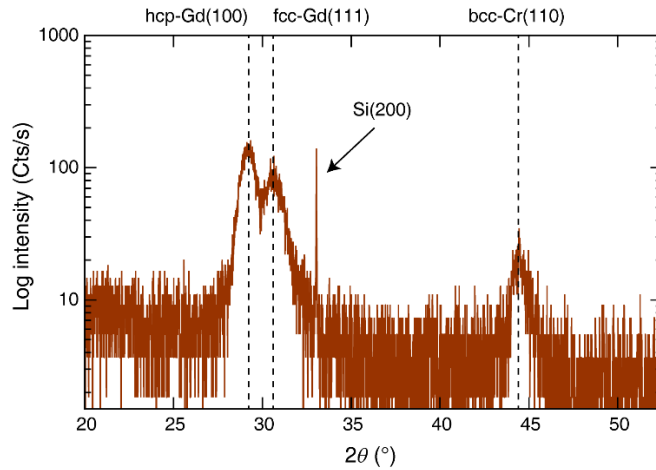
Next, we discuss a possible effect of the B_{EB} on the harmonic Hall measurements in the Co/Cr sample. Note that the B_{EB} acts as an effective magnetic field with a fixed direction, and its magnitude is independent of the AC current in the harmonic Hall measurements. Therefore, it only modifies the external magnetic field B_{ext} . However, the B_{EB} of the Co/Cr sample (~ 1 mT) is much smaller than B_{ext} (≥ 750 mT) for the measurements shown in Fig. 2 of the main text. Therefore, we believe that the B_{EB} effect on the harmonic Hall measurements is not significant. Furthermore, when we conducted the harmonic Hall measurements at 10 K (Fig. 2 of the main text), the samples were cooled down without applying a magnetic field. Thus, the B_{EB} of the Co/Cr sample would have been even smaller than 1 mT, which had hardly affected the harmonic results of the sample.

Furthermore, we theoretically examine if the AFM order in Cr affects the spin and orbital Hall conductivities, $\sigma_{\text{SH}}^{\text{Cr}}$ and $\sigma_{\text{OH}}^{\text{Cr}}$. First, we check the crystal structure of Cr in our sample. Supplementary Figure 6 shows the XRD spectrum of the Gd (10 nm)/Cr (12.5 nm) film, where the diffraction peak at 44.5° corresponds to the Cr (110) plane. This indicates that Cr in the

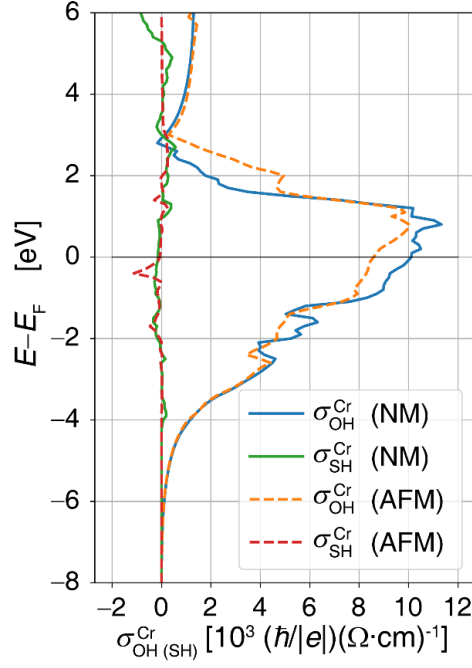
Gd/Cr sample has a bcc structure. Note that the diffraction peaks at 29.2° and 30.7° represent the hcp-Gd (001) and fcc-Gd (111) planes, respectively, indicating that hcp- and fcc-Gd coexist in the Gd/Cr film [9]. We then calculate the $\sigma_{\text{SH}}^{\text{Cr}}$ and $\sigma_{\text{OH}}^{\text{Cr}}$ from electronic band structures of bcc-Cr according to the magnetic order: antiferromagnetic and paramagnetic states. Note that the calculation details are found in literature [5,6]. Supplementary Figure 7 shows the calculated conductivities as a function of the relative energy to the Fermi level ($E-E_F$); the $\sigma_{\text{OH}}^{\text{Cr}}$ is much larger than the $\sigma_{\text{SH}}^{\text{Cr}}$ regardless of the magnetic order, and the $\sigma_{\text{OH}}^{\text{Cr}}$ of the AFM state is slightly smaller than that of the paramagnetic state. The $\sigma_{\text{OH}}^{\text{Cr}}$ and $\sigma_{\text{SH}}^{\text{Cr}}$ values at the Fermi energy are shown in Supplementary Table 1. These results, together with the above experimental results of negligible exchange bias (Supplementary Fig. 5), indicate that the SOT harmonic Hall measurements in our samples were not significantly affected by the AFM order in Cr.



Supplementary Figure 5. Hysteresis loops of the Co (10 nm)/Cr (7.5 nm) (a) and Gd (10 nm)/Cr (7.5 nm) films (b), measured at 10 K after cooling with magnetic field (B_{cooling}) of ± 1 T.



Supplementary Figure 6. XRD spectrum of the Gd (10 nm)/Cr (12.5 nm) film.



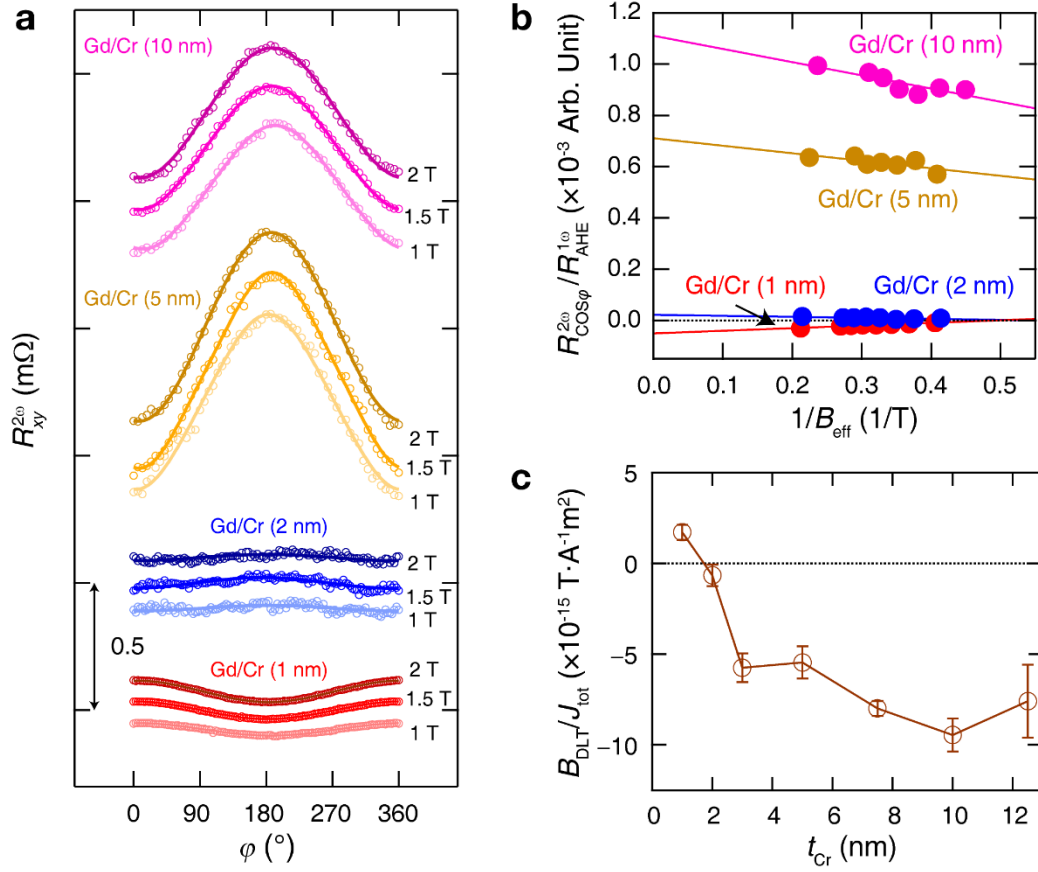
Supplementary Figure 7. Orbital and spin Hall conductivities ($\sigma_{\text{OH}}^{\text{Cr}}$ and $\sigma_{\text{SH}}^{\text{Cr}}$) versus the relative energy to the Fermi level (E_{F}) for antiferromagnetic and paramagnetic Cr.

Supplementary Table 1. Orbital and spin Hall conductivities ($\sigma_{\text{OH}}^{\text{Cr}}$ and $\sigma_{\text{SH}}^{\text{Cr}}$) of Cr at the E_{F} .

Magnetic phase of Cr	AFM	paramagnet
$\sigma_{\text{OH}}^{\text{Cr}} [\times 10^3 (\hbar/e) (\Omega \cdot \text{cm})^{-1}]$	+8.59	+10.11
$\sigma_{\text{SH}}^{\text{Cr}} [\times 10^3 (\hbar/e) (\Omega \cdot \text{cm})^{-1}]$	-0.07	-0.13

Supplementary Note 6: Damping-like torque of Gd/Cr bilayers with Cr thickness

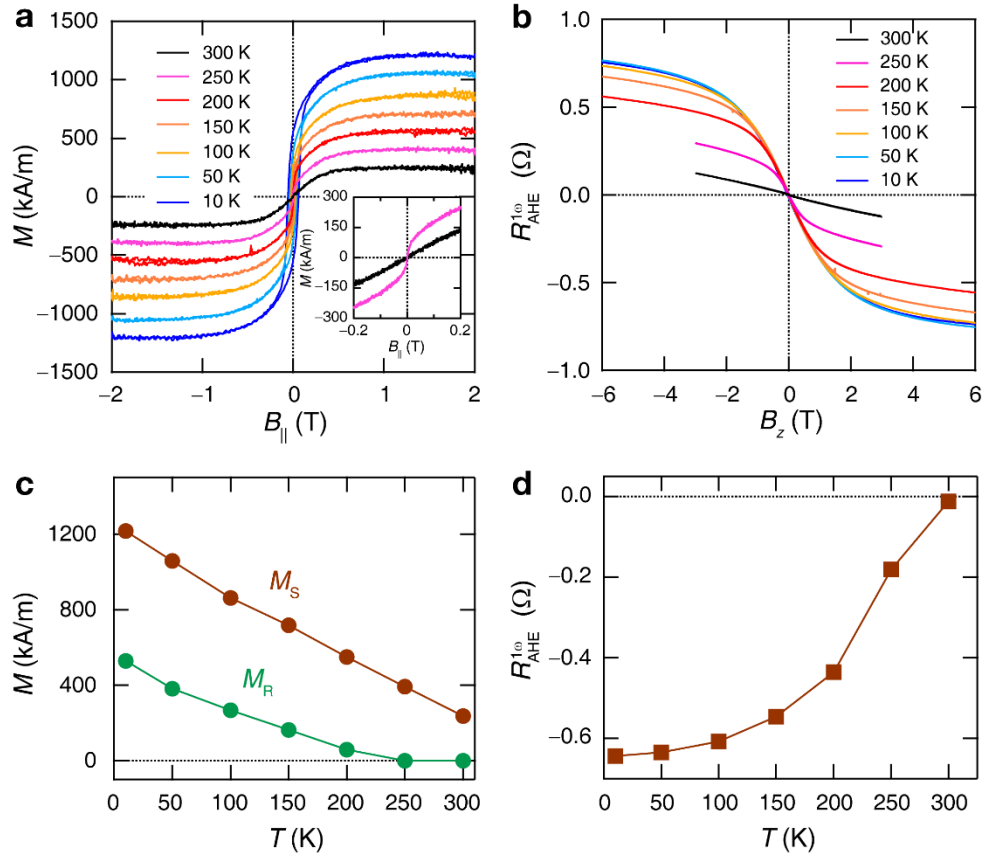
We investigate the spin-orbit torque of Si/SiN_x (200 nm)/Ta (1.5 nm)/Gd (10 nm)/Cr (t_{Cr})/Ta (3 nm) structures with Cr thicknesses (t_{Cr}) of 1~12.5 nm. We repeated the harmonic Hall measurements using the same experimental procedure used in the main text. Supplementary Figure 8a shows 2nd harmonic Hall resistance ($R_{xy}^{2\omega}$) versus azimuthal angle (φ) curves under different external magnetic fields (B_{ext}), where the solid lines are the fitting curves using Eq. 2 of the main text. Supplementary Figure 8b presents the $\cos\varphi$ component of $R_{xy}^{2\omega}$ divided by $R_{\text{AHE}}^{1\omega}$ [$R_{\cos\varphi}^{2\omega}/R_{\text{AHE}}^{1\omega}$] as a function of $1/B_{\text{eff}}$, of which the slope represents damping like torque effective field (B_{DLT}). Supplementary Figure 8c shows the t_{Cr} dependent $B_{\text{DLT}}/J_{\text{tot}}$, where J_{tot} is the current density flowing the total layer including Gd. The B_{DLT} gradually diminishes as t_{Cr} decreases down to 2 nm, which is attributed to the reduced orbital current in a thinner Cr layer (refer Supplementary Fig. 4 above). This result indicates that the B_{DLT} in this thickness range is governed predominantly by the orbital current generated in Cr. On the other hand, when $t_{\text{Cr}}=1$ nm, the sign of B_{DLT} is reversed, which might be caused by the self-torque by Gd. However, in this case, we cannot rule out the spin torque originating from the Ta under and over layers that were introduced to prevent oxidation of the Gd layer. Thus, further investigation with elaborated structures is required to explicitly resolve the self-torque by Gd.



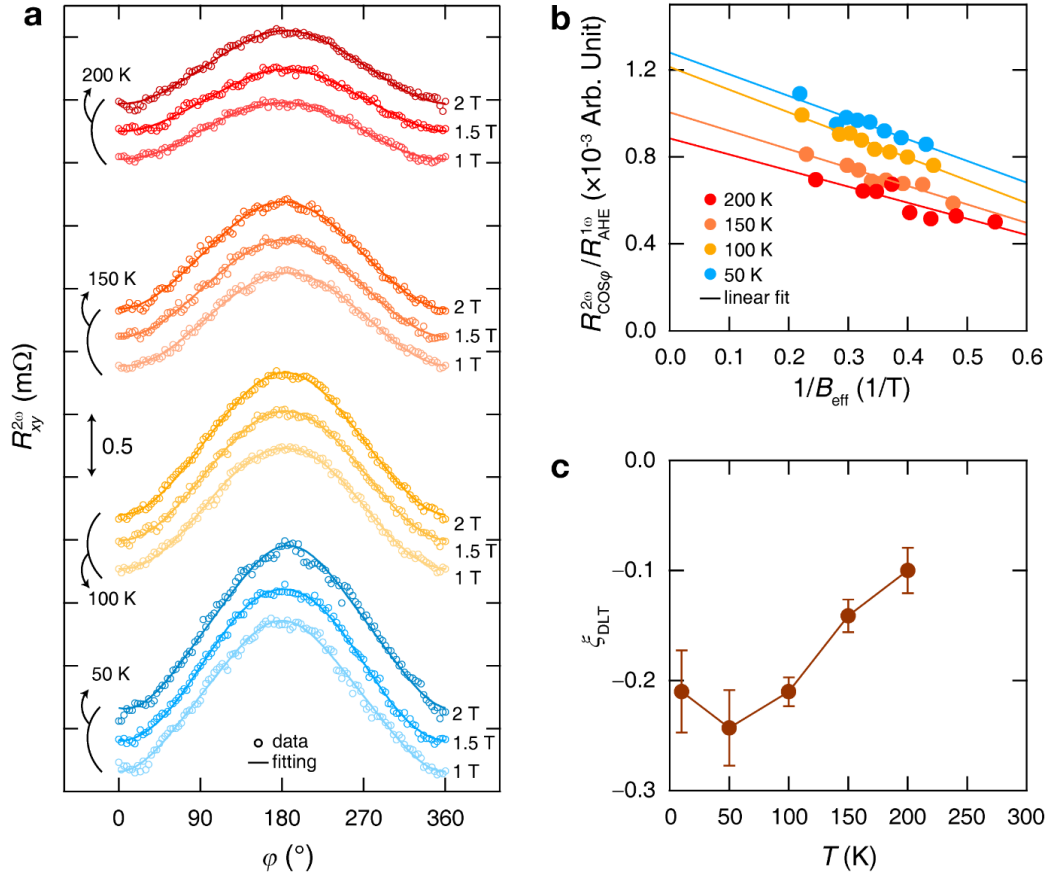
Supplementary Figure 8. **a**, Azimuthal angle (ϕ) dependent 2nd harmonic Hall resistance, $R_{xy}^{2\omega}(\phi)$, under different external magnetic field (B_{ext}) of the representative Gd (10 nm)/Cr (1, 2, 5, and 10 nm) Hall-bar patterned samples. The solid lines are the fitting curves using Eq. 2 in the main text. **b**, Cr thickness (t_{Cr}) dependent $R_{\cos\phi}^{2\omega}/R_{\text{AHE}}^{1\omega}$ as function of $1/B_{\text{eff}}$. Each solid line is the linear fitting line. **c**, Cr thickness (t_{Cr}) dependent damping-like effective field normalized by the current density ($B_{\text{DLT}}/J_{\text{tot}}$) of the Gd/Cr samples. All data were obtained at 10 K.

Supplementary Note 7: Temperature-dependent damping-like torque of Gd/Cr bilayers

We investigate the temperature-dependent damping-like torque efficiency (ξ_{DLT}) of the Gd (10 nm)/Cr (7.5 nm) sample. We first measure the temperature-dependent magnetization and anomalous Hall resistance ($R_{\text{AHE}}^{1\omega}$), which are shown in Supplementary Figs. 9a and 9b, respectively. Note that the magnetization (anomalous Hall resistance) is measured with an in-plane (out-of-plane) magnetic field. Supplementary Figure 9c and 9d summarize the remanence and saturation magnetizations (M_{R} and M_{S}) and anomalous Hall resistance (R_{AHE}) as a function of the measurement temperature, respectively. The zero M_{R} at 250 K indicates that the Curie temperature of Gd in our sample is between 200 K and 250 K. We then perform the harmonic Hall measurements at various temperatures below 200 K. Supplementary Figure 10a shows the azimuthal angle-dependent 2nd harmonic Hall resistances, $R_{xy}^{2\omega}(\varphi)$, under different external magnetic fields, B_{ext} 's, where the solid lines are the fitting curves using Eq. 2 of the main text. Supplementary Figure 10b presents the $\cos \varphi$ -component of $R_{xy}^{2\omega}$ divided by $R_{\text{AHE}}^{1\omega}$ [$R_{\cos\varphi}^{2\omega}/R_{\text{AHE}}^{1\omega}$] as a function of $1/B_{\text{eff}}$. Here, B_{eff} is the effective magnetic field, including the demagnetization field and anisotropy field of ferromagnet. The damping-like effective field (B_{DLT}) is extracted from the slope of the $R_{\cos\varphi}^{2\omega}/R_{\text{AHE}}^{1\omega}$ versus $1/B_{\text{eff}}$. We then estimate $\xi_{\text{DLT}} = (2e/\hbar)(M_{\text{S}}t_{\text{Gd}}B_{\text{DLT}}/J_{\text{Cr}})$, where, e is the electron charge, $\hbar$ is the reduced Planck constant, M_{S} is the saturation magnetization, t_{Gd} is the Gd thickness, and J_{Cr} is the current density flowing through the Cr layer. Supplementary Figure 10c shows the temperature-dependent ξ_{DLT} of the Gd/Cr sample, demonstrating that the magnitude of ξ_{DLT} increases with decreasing temperature. The temperature dependence of the orbital-current-induced ξ_{DLT} can be attributed to phonon scattering since the orbital angular momentum is strongly coupled to the lattice through the crystal field potential [6]. As the temperature increases, more phonons are generated, reducing the orbital Hall effect. Note that a similar temperature dependence of the orbital-current-induced torque has also been reported in the literature [10,11]. They also observed a large enhancement of the orbital-current-induced torque in the naturally-oxidized-Cu/Ni₈₁Fe₁₉ or Pt/Co/SiO₂ sample with decreasing temperature, which was explained by the phonon scattering mechanism.



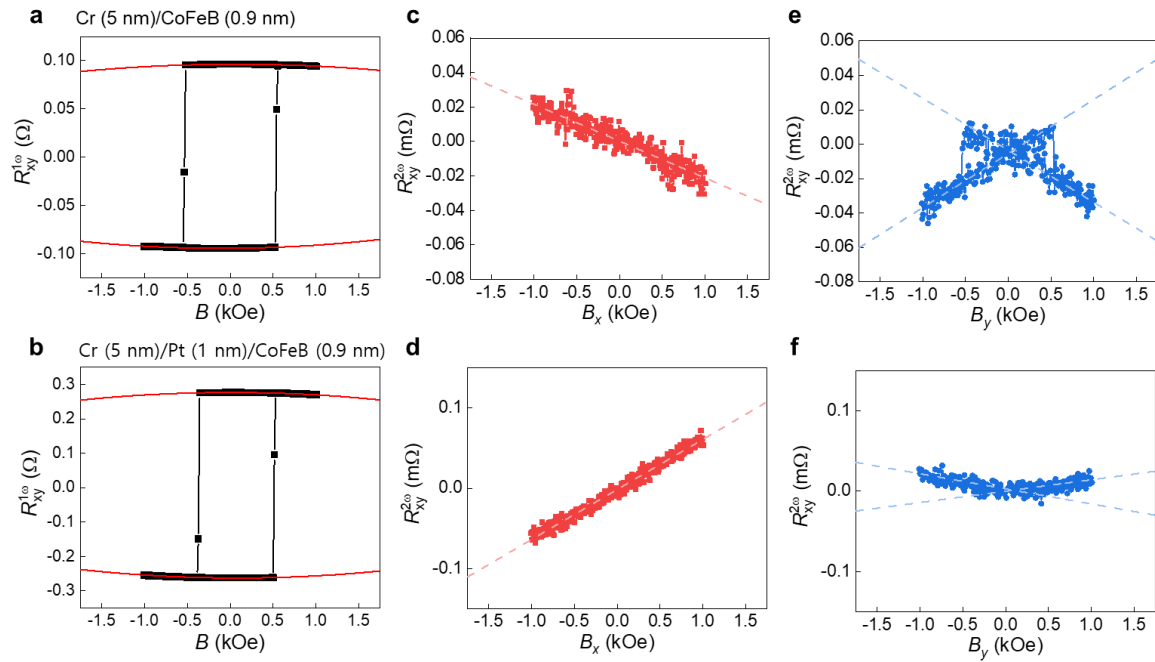
Supplementary Figure 9. **a**, Temperature-dependent hysteresis loops of the Gd (10 nm)/Cr (7.5 nm) sample. Inset shows paramagnetic hysteresis loops at $T=250$ K (pink) and 300 K (black). **b**, Temperature-dependent anomalous Hall effect ($R_{\text{AHE}}^{1\omega}$) of the Gd/Cr Hall-bar patterned sample. **c**, Remanence (M_R) and saturation magnetization (M_S) as a function of temperature. **d**, Anomalous Hall resistance ($R_{\text{AHE}}^{1\omega}$) as a function of temperature.



Supplementary Figure 10. **a**, Azimuthal angle (φ) dependent 2nd harmonic Hall resistance, $R_{xy}^{2\omega}(\varphi)$, under different external magnetic field (B_{ext}) of the Gd (10 nm)/Cr (7.5 nm) Hall-bar patterned sample, measured at different temperatures ranging from 50 to 200 K. The solid lines are fitting curves using Eq. 2 in the main text. **b**, Temperature-dependent $R_{\cos\varphi}^{2\omega}/R_{\text{AHE}}^{1\omega}$ as function of $1/B_{\text{eff}}$. Each solid line is a linear fitting line. **c**, Temperature-dependent damping-like torque efficiency (ξ_{DLT}) of the Gd/Cr sample.

Supplementary Note 8: Perpendicular harmonic Hall measurement of Cr/CoFeB and Cr/Pt/CoFeB samples.

We perform the perpendicular harmonic Hall measurements to investigate the SOT effective fields for the two samples of Cr (5 nm)/CoFeB (0.9 nm) and Cr (5 nm)/Pt (1 nm)/CoFeB (0.9 nm) structures [12,13]. Supplementary Figures 11a,b show the 1st harmonic Hall resistance ($R_{xy}^{1\omega}$) as a function of in-plane magnetic fields, representing the out-of-plane magnetization component. Supplementary Figures 11c,d and 11e,f show the 2nd harmonic Hall resistance ($R_{xy}^{2\omega}$) obtained while sweeping in-plane magnetic fields along (B_x) and transverse (B_y) to the current direction, respectively. Here, an applied current density is 1×10^{11} A/m². The slope of the $R_{xy}^{2\omega}$ versus B_x (B_y) represents the sign of B_{DLT} (B_{FLT}). We observe that the Cr/CoFeB (Cr/Pt/CoFeB) sample has a negative (positive) slope, which is consistent with the SOT switching polarity (Fig. 3 in the main text).

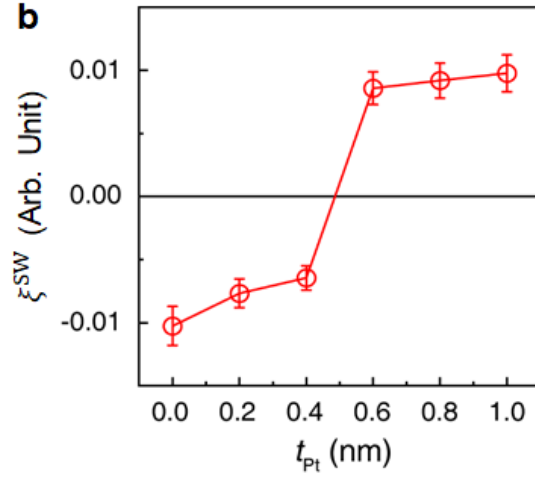
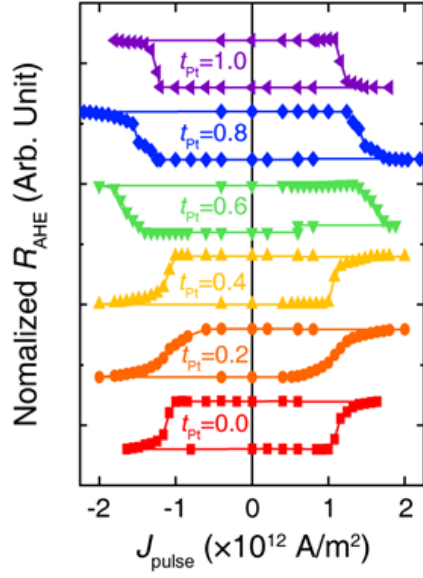


Supplementary Figure 11. Harmonic Hall measurements of the Cr/CoFeB and Cr/Pt/CoFeB samples. **a,b**, The 1st harmonic Hall resistance ($R_{xy}^{1\omega}$) for the Cr (5 nm)/CoFeB (0.9 nm) (**a**) and Cr (5 nm)/Pt (1 nm)/CoFeB (0.9 nm) (**b**) samples. **c,d**, The 2nd harmonic Hall resistance ($R_{xy}^{2\omega}$) versus in-plane magnetic field (B_x) along the current direction for the Cr/CoFeB (**c**) and Cr/Pt/CoFeB (**d**) samples. **e,f**, The $R_{xy}^{2\omega}$ versus in-plane magnetic field (B_y) transverse to the current direction for the Cr/CoFeB (**e**) and Cr/Pt/CoFeB (**f**) samples. Dotted lines represent the linear fits. The B_x and B_y are applied with a slight polar angle ($\theta=5^\circ$) from the film plane to prevent the multi-domain formation.

Supplementary Note 9: Orbital-to-spin conversion efficiency with Pt thickness

We examine the orbital-to-spin conversion efficiency as a function of Pt thickness (t_{Pt}) in Cr/Pt (t_{Pt})/FM heterostructures. Here, the t_{Pt} is varied from 0 nm to 1.0 nm, where all samples have perpendicular magnetic anisotropy. We first perform the current-induced magnetization switching for Cr (5.0 nm)/Pt (t_{Pt})/CoFeB (0.9 nm) structures with the same experiment procedure shown in Fig. 3 of the main text. Supplementary Figure 12a exhibits the SOT-induced switching curves as a function of a pulse current density (J_{pulse}) for the samples. Note that an in-plane magnetic field (B_x) of +20 mT is applied along the current direction for deterministic switching. From the switching current density J_{SW} , we calculate the switching efficiency $\xi^{\text{SW}} = \left(\frac{2e}{\hbar}\right) \left(\frac{M_S t_{\text{CoFeB}} B_P}{J_{\text{SW}}}\right)$ [14], where M_S is the saturation magnetization, t_{CoFeB} is the CoFeB thickness, B_P is the domain wall propagation field. Supplementary Figure 12b shows ξ^{SW} versus t_{Pt} ; when $t_{\text{Pt}} \leq 0.4$ nm, the ξ^{SW} is negative, which is consistent with the negative spin Hall angle of Cr. This indicates that the spin Hall effect (SHE) of Cr plays a dominant role in magnetization switching in this thickness regime. Interestingly, the switching polarity is abruptly reversed as the t_{Pt} increases above 0.6 nm. The positive ξ^{SW} or positive $\theta_{\text{SH}}^{\text{eff}}$ is the expected sign in the OHT scenario (Fig. 3a of the main text), where the orbital current originating from Cr is converted to spin current in the Pt layer. Since Pt has a positive orbital-spin conversion coefficient (η_{L-S}^{Pt}), $\theta_{\text{SH}}^{\text{eff}}$ becomes positive ($\theta_{\text{SH}}^{\text{eff}} \propto \sigma_{\text{OH}}^{\text{Cr}} \eta_{L-S}^{\text{Pt}}$), where $\sigma_{\text{OH}}^{\text{Cr}}$ is the orbital Hall conductivity of Cr. These results indicate that the orbital Hall effect is dominant over the spin Hall effect when t_{Pt} is greater than 0.6 nm, where Pt forms a continuous film that effectively converts orbital currents to spin currents. Note that the sign change of the ξ^{SW} occurs at a t_{Pt} between 0.4 and 0.6 nm, which is much smaller than the spin diffusion length of Pt [15]. This result demonstrates that the sign change in $\theta_{\text{SH}}^{\text{eff}}$ is not caused by the interfacial Pt with a positive spin Hall angle.

a Cr (5 nm)/Pt (t_{Pt} nm)/CoFeB (0.9 nm)

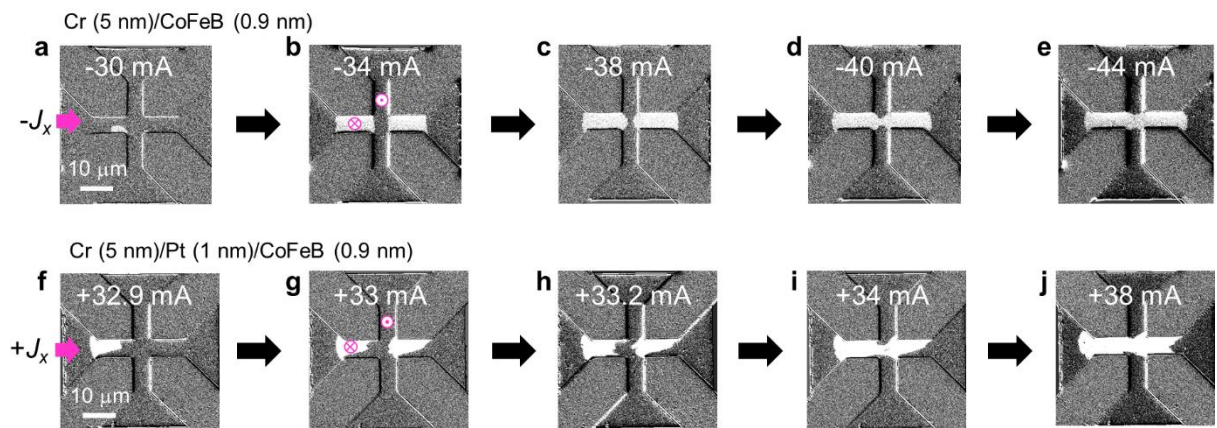


Supplementary Figure 12. Pt thickness dependence of orbital Hall torque driven magnetization switching in Cr/Pt/CoFeB heterostructures. **a**, Magnetization switching curves of Cr (5 nm)/Pt (0 ~ 1 nm)/ CoFeB (0.9 nm) samples under a B_x of +20 mT. **b**, t_{Pt} -dependent switching efficiency (ξ^{SW}) of the Cr/Pt/CoFeB samples. The line is a guide to eyes. All measurements are conducted at 300 K.

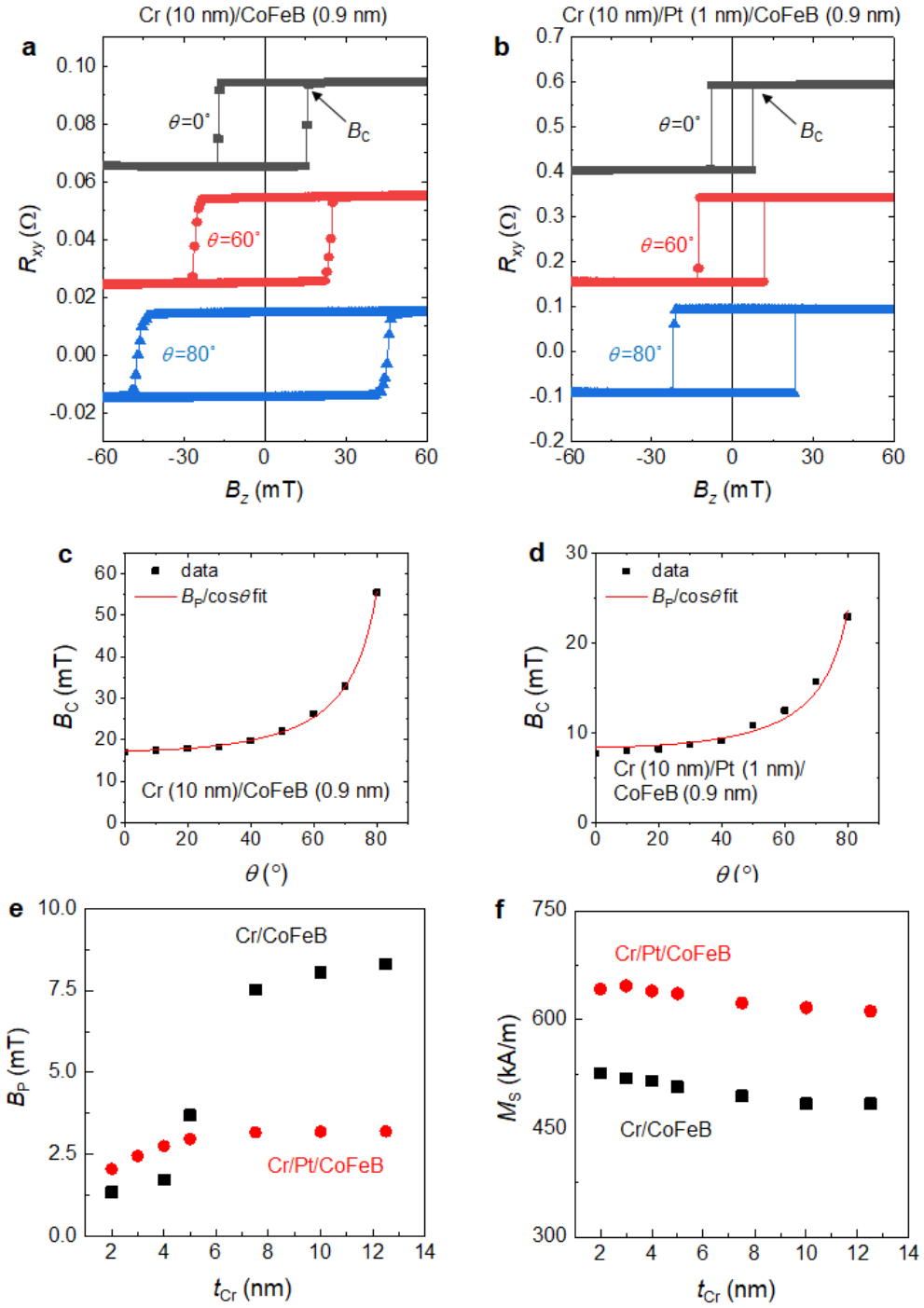
Supplementary Note 10: Current-induced SOT switching mechanism

In order to investigate the current-induced magnetization switching mechanism, we perform the magneto-optic Kerr effect (MOKE) measurement of the Cr (5 nm)/CoFeB (0.9 nm) and Cr (5 nm)/Pt (1 nm)/CoFeB (0.9 nm) samples. The intermediated domain images of the samples during the current-induced switching are captured after each pulse current under a constant external magnetic field ($B_x = +20$ mT) along the current direction. Supplementary Figures 13a,b show the results; the magnetic domain of down magnetization (light contrast in the MOKE image) firstly nucleates at the outside of the Hall-cross and propagates into the Hall-cross region with increasing the pulse current (J_x). Note that negative (positive) current prefers down magnetization for the Cr/CoFeB (Cr/Pt/CoFeB) samples. This demonstrates that the magnetization switching of the Cr/CoFeB and Cr/Pt/CoFeB samples is governed by the current-induced domain nucleation and domain wall propagation [16].

We also measure domain wall propagation field (B_P) and saturation magnetization (M_S) of the Cr/CoFeB and Cr/Pt/CoFeB samples to evaluate the switching efficiency (ξ^{SW}). Supplementary Figures 14a,b show anomalous Hall resistance (R_{xy}) of the samples at various polar angles θ 's of the magnetic field, demonstrating the θ -dependent coercive field B_C . From the B_C versus θ curves (Supplementary Figures 14c,d), we extract the domain wall propagation field B_P using the relation of $B_C = B_P / \cos\theta$ [14]. Supplementary Figures 14e,f show the obtained B_P and M_S of Cr/CoFeB and Cr/Pt/CoFeB samples as a function of the t_{Cr} , respectively.



Supplementary Figure 13. MOKE images of domain wall nucleation and propagation during the SOT switching. a-j, MOKE images captured after current pulses of Cr (5 nm)/CoFeB (0.9 nm) (a-e) and Cr (5 nm)/Pt (1 nm)/CoFeB (0.9 nm) (f-j) samples.



Supplementary Figure 14. Estimation of domain wall propagation field and saturation magnetization. **a,b**, The representative polar angle (θ) dependent of anomalous Hall resistance (R_{xy}) of Cr (10 nm)/CoFeB (0.9 nm) (**a**) and Cr (10 nm)/Pt (1 nm)/CoFeB (0.9 nm) (**b**). The switching field (B_c) is denoted by an arrow. **c,d**, The θ dependent B_c of Cr (10 nm)/CoFeB (0.9 nm) (**c**) and Cr (10 nm)/Pt (1 nm)/CoFeB (0.9 nm) (**d**). The solid curves indicate the fitting using $B_P/\cos(\theta)$. **e,f**, Domain wall propagation field (B_P) and saturation magnetization (M_S) as a function of t_{Cr} for Cr/CoFeB (black squares) and Cr/Pt/CoFeB (red circles) samples.

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