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Electrical Switching of Tri-State Antiferromagnetic Néel Order in α -Fe₂O₃ Epitaxial Films

Yang Cheng^{1,*}, Sisheng Yu^{1,*}, Menglin Zhu², Jinwoo Hwang², Fengyuan Yang¹

¹Department of Physics, The Ohio State University, Columbus, OH, 43210 USA

²Department of Materials Science and Engineering, The Ohio State University, Columbus, OH, 43212, USA

*These two authors contributed equally to this work.

We demonstrate non-decaying, step-like electrical switching of tri-state Néel order in Pt/ α -Fe₂O₃ bilayers detected by spin-Hall induced anomalous Hall effect. The as-grown Pt/ α -Fe₂O₃ bilayers exhibit saw-tooth switching behavior generated by current pulses. After annealing by a high pulse current, the Hall signals reveal single-pulse saturated, non-decaying, step-like switching. Together with control experiments, we show that the saw-tooth switching is due to an artifact of Pt while the actual spin-orbit torque induced antiferromagnetic switching is step-like. Our Monte-Carlo simulations explain the switching behavior of α -Fe₂O₃ Néel order among three in-plane easy axes.

Spin-orbit torque (SOT) induced switching of ferromagnets (FM) by an adjacent heavy metal (HM) has raised wide interests in recent years,¹⁻³ where a charge current in the HM generates spins at the HM/FM interface via the spin Hall effect (SHE). Antiferromagnets (AFs) offer the advantage of no stray field, robustness against external field, THz response, and abundance of material selections.⁴⁻¹² It has been predicted that Néel SOT can be utilized to switch AF spins in picoseconds for THz operations.¹³⁻¹⁷ Electrical switching of bi-state AF moments has been demonstrated in metallic AFs, CuMnAs and Mn₂Au.¹⁸⁻²² For antiferromagnetic insulators (AFIs), the switching of Néel order can be achieved in HM/AFI bilayers by damping-like SOT, as shown recently in Pt/NiO bilayers with saw-tooth shaped switching, which was interpreted as that every ~ 1 ms current pulse can flip the AF-Néel order incrementally.²³⁻²⁶ In this letter, we report the first observation of tri-state, step-like switching of Néel order in Pt(2 nm)/ α -Fe₂O₃(30nm) bilayers grown on Al₂O₃(001) substrates, which is read out by Hall resistance (ΔR_{xy}) detection. Our results demonstrate that the saw-tooth ΔR_{xy} is an artifact from the Pt layer, while the SOT-induced AF switching is step-like.

Epitaxial α -Fe₂O₃ films are grown on Al₂O₃(001) substrates using off-axis sputtering,²⁷⁻²⁹ followed by in-situ deposition of a Pt layer on α -Fe₂O₃ at room temperature.^{30, 31} α -Fe₂O₃ is a high temperature AFI with a corundum structure as shown in Fig. 1(a). The Fe³⁺ moments stay in the (001) plane and stack antiferromagnetically along the *c*-axis above the Morin transition temperature^{32, 33} (see Supplementary Materials³⁴, which includes Refs.³⁵⁻³⁸). Figure 1(b) shows a $2\theta/\omega$ X-ray diffraction (XRD) scan of an α -Fe₂O₃(30 nm) epitaxial film on Al₂O₃(001), where the Laue oscillations of the α -Fe₂O₃(006) peak in the inset indicate its high quality. The scanning transmission electron microscopy (STEM) image of a Pt(2 nm)/ α -Fe₂O₃(30 nm) bilayer shown in Fig. 1(c) reveals the single-crystalline ordering of α -Fe₂O₃ and the clean Pt/Fe₂O₃

interface.

Figure 2(a) shows the ab -plane of α -Fe₂O₃ hexagonal lattice with three easy axes along [210], [120], and $[1\bar{1}0]$.^{32, 39} We pattern our Pt(2 nm)/ α -Fe₂O₃(30nm) bilayers into 8-leg Hall crosses, as shown in Figs. 2(b) and 2(c), where the width of the two vertical Hall terminals is 5 μ m and the other six legs (60° apart) are 10 μ m wide. We determine the crystallographic axes of the samples using reflection high-energy electron diffraction (RHEED) to align **E1**, **E2**, and **E3** with the [210], [120], and $[1\bar{1}0]$ easy axes of α -Fe₂O₃, respectively (see Supplementary Materials³⁴).

Hall resistances of the patterned bilayers are measured using a Physical Property Measurement System (PPMS) at 300 K unless specified otherwise. During our switching measurements, we first apply a 1-ms pulse current (I_p) along one of three easy axes, wait for 30 seconds, and then measure the Hall voltage across the two vertical terminals by sending a small sensing current (I_s) of 100 μ A along **E2**. After a series of 10 pulses, we change the direction of I_p to another easy axis and repeat the measurement. Figure 2(d) shows ΔR_{xy} as a function of pulse count at $I_p = 9$ mA (current density, $j = 4.5 \times 10^7$ A/cm²), which exhibits clean tri-state Hall resistances at $I_p \parallel \mathbf{E1}$ (low), $I_p \parallel \mathbf{E2}$ (intermediate), and $I_p \parallel \mathbf{E3}$ (high) as I_p is switched from **E2**→**E3**→**E2**→**E1**→**E2**. This switching behavior can be understood as follows: 1) when an initial pulse current is applied along one of the three easy axes, the damping-like SOT rotates the Néel order $\mathbf{n}$ to align with I_p ,²³ 2) a small sensing current is sent along **E2** and a spin-Hall induced anomalous Hall effect (SH-AHE) voltage is measured, which reflects the orientation of $\mathbf{n}$, 3) after the first pulse, the subsequent 9 pulses cause essentially no change in $\mathbf{n}$, resulting in a plateau, 4) as I_p is changed to a new easy axis, $\mathbf{n}$ aligns with the new direction of I_p , leading to a step-jump of ΔR_{xy} . The step-like switching of the Néel order is in distinct contrast with previous

reports in Pt/NiO bilayers with saw-tooth shaped ΔR_{xy} .

The magnitude of the Hall resistance, $\Delta R_{xy}(\mathbf{E3}) > \Delta R_{xy}(\mathbf{E2}) > \Delta R_{xy}(\mathbf{E1})$ arises from the relative angle of -60° , 0° , and $+60^\circ$ between $\mathbf{n}$ and $\mathbf{I}_s$ (which generate spins $\boldsymbol{\sigma} \perp \mathbf{I}_s$ in Pt via SHE) for $\mathbf{I}_p$ along $\mathbf{E3}$, $\mathbf{E2}$, and $\mathbf{E1}$, respectively, as expected from the angular dependence of the damping-like SOT induced SH-AHE.^{23, 26, 40} To corroborate the results in Fig. 2(d), we use an independent approach to control the Néel order by an applied field ($\mathbf{H}$) which aligns $\mathbf{n} \perp \mathbf{H}$ via the in-plane spin-flop (SF) transition once H exceeds the SF field. Figure 2(e) shows the angular dependence of ΔR_{xy} by applying an in-plane field (see Fig. 2(c) where α is the angle between $\mathbf{H}$ and $\mathbf{E2}$ or $[120]$ crystal axis) of 0.1, 1, and 3 T, which is analogous to the planar Hall measurement in FMs. At $H \geq 1$ T, ΔR_{xy} reaches saturation and follows $\sin 2\alpha$, while at $H = 0.1$ T, it shows an irregular angular dependence, indicating that the in-plane SF transition in our α -Fe₂O₃ films occurs at below 1 T with $\mathbf{n} \perp \mathbf{H}$.^{40, 41} The peak-to-valley magnitude of ΔR_{xy} in Fig. 2(e) is 0.27 Ω , which gives the upper limit of Hall resistance change in Pt/ α -Fe₂O₃ switching measurement. The plateaus in Fig. 2(d) for E3, E2, and E1 correspond to $\alpha = 30^\circ$, 90° , and 150° marked in Fig. 2(e), respectively. The values of ΔR_{xy} in Fig. 2(d) are smaller as compared to the corresponding points in Fig. 2(e), and we will explain it below in Fig. 4.

Because for damping-like SOT $\propto \mathbf{n} \times (\mathbf{j} \times \hat{\mathbf{z}}) \times \mathbf{n}$, the magnitude of pulse current density $\mathbf{j}$ determines ΔR_{xy} ,²³ we measure the I_p dependence of the Pt/ α -Fe₂O₃ samples by applying $\mathbf{I}_p$ along E1 and E3, as shown in Fig. 3(a). As I_p increases, ΔR_{xy} changes from single-pulse saturation, step-like switching to saw-tooth shaped switching. At $I_p = 16$ mA, there is a clear decay of ΔR_{xy} after several cycles of pulses. During the first cycle, ΔR_{xy} is $\sim 0.3 \Omega$ which is above the upper limit of 0.27 Ω given by Fig. 2(e). The obvious decay at $I_p = 16$ mA has been observed in other HM/AFI switching systems, which was attributed to the decrease of switching

efficiency.^{19, 24}

To uncover the cause of saw-tooth switching and the decay of ΔR_{xy} , we perform the same measurement using another Hall cross on the same sample in an in-plane field of 3 T applied at $\mathbf{H} \perp \mathbf{E2}$ [Fig. 3(b)]. Since $\mathbf{H}$ is fixed at $\alpha = 90^\circ$ and above the SF field, the AF moments are frozen along $\mathbf{E2}$ and no switching is expected. Surprisingly, the 3 T field has essentially no impact on ΔR_{xy} at $I_p = 16$ mA, which remains saw-tooth like with similar magnitude. The 12 and 10 mA curves, on the other hand, shows sharp difference, becoming flat lines (no switching) in Fig. 3(b). The inset in Fig. 3(b) plots ΔR_{xy} vs. I_p in a semi-log scale, exhibiting an exponential dependence. Likewise, the inset in Fig. 3(a) shows a similar plot for 0 T, where the red curve is not a fit, but the sum of exponential fit obtained in the inset of Fig. 3(b) and the linear fit from Fig. 4(c) below.

To highlight the contrast between Figs. 3(a) and 3(b), Figs. 3(c) and 3(d) show the comparison of ΔR_{xy} between the 0 and 3 T data at $I_p = 16$ and 12 mA, respectively. In Fig. 3(c) for $I_p = 16$ mA, there is essentially no difference between the 0 and 3 T curves despite the different AF spin configurations. In Fig. 3(d) for $I_p = 12$ mA, the 3 T field turns the step-like ΔR_{xy} at 0 T into an essentially flat line (with a very small but non-negligible saw-tooth shape), suggesting that the step-like switching is the real AF switching while the saw-tooth feature has a different origin.

Considering the saw-tooth feature is most obvious at $I_p = 16$ mA, we apply an even higher pulse current of 18 mA ($j = 9.0 \times 10^7$ A/cm²) at zero field to anneal the 2 nm Pt layer and then redo the measurement at $I_p = 16$ and 12 mA in a 3 T field, as shown in Figs. 3(e) and 3(f), respectively. In both cases, there is no switching and ΔR_{xy} remains flat after the annealing. We next perform the same measurement at zero field for $I_p = 16$ and 12 mA. Figure 3(g) shows that

after the annealing, the saw-tooth curve at $I_p = 16$ mA is transformed to a step-like switching. In Fig. 3(h) for $I_p = 12$ mA, ΔR_{xy} remains step-like while the switching becomes more square-like. This result demonstrates that the annealing dramatically changes the detected switching behavior, which we attribute to the improved stability of the Pt(2 nm) layer after the annealing.

Since the switching of Pt/ α -Fe₂O₃ samples becomes significantly more stable after the annealing, we can obtain a reliable I_p dependence of the SOT-induced switching. Figure 4(a) shows that for the whole current range from 6 to 16 mA, ΔR_{xy} exhibits step-like switching with high stability and no detectable decay. The onset of switching occurs at $I_p = 6$ mA or $j = 3.0 \times 10^7$ A/cm², comparable to the values for typical HM/FM systems.^{2,3} A linear-scale plot of ΔR_{xy} vs. I_p shown in Fig. 4(c) exhibits a linear dependence at $I_p \geq 8$ mA. This indicates the SOT responsible for the AF switching is linearly proportional to the magnitude of I_p , which in turn is proportional to the SHE-generated spin accumulation at the Pt/ α -Fe₂O₃ interface. In addition, the fitting parameters obtained from Fig. 4(c), together with the exponential fitting to the inset in Fig. 3(b), are used to create the red curve in the inset in Fig. 3(a), which approximately agrees with the experimental data for fresh samples without the annealing.

During the switching of $\mathbf{n}$ from one easy axis to another, thermal fluctuation is expected^{19, 26} to help $\mathbf{n}$ overcome the potential barrier due to magnetocrystalline anisotropy. We measure the temperature (T) dependence of ΔR_{xy} at $I_p = 9$ mA from 200 to 300 K at zero field as shown in Fig. 4(b), which decreases at lower temperatures as expected. Figure 4(d) shows the ΔR_{xy} vs. T plot, which exhibits an exponential dependence, confirming thermally activated AF switching.¹⁹

Figure 4(e) shows the dependence of ΔR_{xy} on the magnitude of an in-plane field applied at $\mathbf{H} \perp \mathbf{E}_3$, [$\alpha = 30^\circ$, see Fig. 2(c)], which aligns $\mathbf{n} \parallel \mathbf{E}_3$ at H above the SF field. As H is ramped from 0 to 1 T (initial curve) and then back to 0 T, the ΔR_{xy} vs. H curve exhibits a full loop in the

first-quadrant, analogous to FMs. The remanence of ΔR_{xy} at $H = 0$ T on the red curve is $\sim 25\%$ of the saturation value at 1 T because the α -Fe₂O₃ film transitions from a single domain to multi-domains as H is reduced to below the SF field. We also perform a minor loop measurement by ramping H from 0 to 0.1 T and then back to 0 T, which exhibits a much smaller remanence at 0 T.

A pulse current applied along an easy axis generates SHE-induced spin accumulation near the Pt/ α -Fe₂O₃ interface, which acts as an effective magnetic field $\propto (\mathbf{j} \times \hat{\mathbf{z}}) \times \mathbf{n}$ and exerts a SOT on the Néel order to align $\mathbf{n}$ with $\mathbf{I}_p$. This is similar to an FM whose magnetization can be aligned by a magnetic field. Given the THz response of AFs¹³ and that the sample temperature can be stabilized in μs ,¹⁹ a single 1-ms pulse is long enough for an AF to reach equilibrium. As a result, the percentage of Néel order switching only depends on the magnitude of I_p rather than the number of pulses. Since our ΔR_{xy} is recorded using a small sensing current long after the pulse current is off, the measured signal is the remanence of ΔR_{xy} , which is a fraction of the saturation value. This is analogous to the demagnetization process of FMs and can explain why ΔR_{xy} in switching measurements is much smaller than that in the field-dependence measurements shown in Fig. 2(e).

Figure 4(f) shows our Monte-Carlo simulations of the full and minor loops in Fig. 4(e) by computing the component of $\mathbf{n}$ along $\mathbf{E}_3$, n_{E3} , as a function of the effective magnetic field, $H_{eff}/\sqrt{2H_{k2}}$, generated by the SOT with $\mathbf{I}_p \parallel \mathbf{E}_3$, where H_{k2} is the easy-plane anisotropy field (see Supplementary Materials³⁴ for details). The simulation result of SOT-induced switching qualitatively agrees with the experiment result in Fig. 4(e) induced by an external field, revealing the similarities in the control of AF spins between a magnetic field and current-induced SOT.

To uncover the reason for the saw-tooth switching, we perform the switching measurements for a Pt(2 nm) film directly deposited on Al₂O₃ and SrTiO₃ (see Supplementary

Materials³⁴), which display the saw-tooth shaped ΔR_{xy} . We speculate that the saw-tooth feature of ΔR_{xy} is due to the current-driven migration of grain boundaries in thin Pt layers. This proves that the saw-tooth feature is an artifact⁴² due to Pt and not related to the AF switching, while the actual AF switching exhibits single-pulse saturation, step-like Hall resistance, which disappears after the AF spins are “frozen” by a magnetic field. As a comparison, we also try electrical switching of a Pt/Cr₂O₃ bilayer (see Supplementary Materials³⁴), which does not exhibit AF switching because the Cr₂O₃ epitaxial film is an AF with an out-of-plane uniaxial anisotropy. Our results point to a promising path toward controlling AF spins in insulating AFs using spin-orbit torque. Also, we proposed a criterion to separate the SOT switching from the artifacts, where a real AF switching is unattenuated and can be suppressed by a magnetic field when exceeding the spin-flop field.

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Figure Captions:

Figure 1. (a) Schematic of the α -Fe₂O₃ hexagonal lattice with FM-aligned Fe moment in the ab -plane and AF coupling between adjacent ab -planes (oxygen atoms not shown). (b) $2\theta/\omega$ XRD scan of a 30 nm α -Fe₂O₃ epitaxial film on Al₂O₃(001). The insert shows a zoom-in region around the α -Fe₂O₃(006) peak. (c) STEM image of a Pt(2 nm)/ α -Fe₂O₃(30 nm) bilayer.

Figure 2. (a) The ab -plane of α -Fe₂O₃ lattice with three in-plane easy axes, [210], [120], and [1 $\bar{1}$ 0] labeled as E1, E2 and E3, resulting in a tri-axial anisotropy, where the double arrows represent the AF spins. (b) Optical microscopy image and (c) schematic of an eight-leg Hall cross of a Pt(2 nm)/ α -Fe₂O₃(30nm) bilayer, where α is the angle between an in-plane field and the E2 direction. (d) A sequential pulse current of $I_p = 9$ mA is applied along one of the three easy axes (10 pulses for each segment) at 300 K and a reversible control of tri-state Hall resistance is detected by applying a 0.1 mA sensing current along E2. (e) In-plane α dependence of ΔR_{xy} at $H = 0.1, 1$, and 3 T, where ΔR_{xy} saturates at $H \geq 1$ T. The gray and purple solid curves are $\sin 2\alpha$ fits.

Figure 3. Evolution of ΔR_{xy} when the pulse current is switched between E3 and E1 (10 pulses each) under (a) 0 T and (b) 3 T in-plane field applied perpendicular to E2 for a Pt(2 nm)/ α -Fe₂O₃(30 nm) bilayer. Insets: semi-log plots of ΔR_{xy} vs. I_p . The red line in inset (b) is an exponential fit, $y = (1.38 \times 10^{-11})e^{1.44x}$, and the red curve in inset (a) is given by, $y = (1.38 \times 10^{-11})e^{1.44x} + (-0.0183 + 0.00243x)$, which is the sum of the exponential fit in inset (a) here and the linear fit in Fig. 4(c). Comparison of ΔR_{xy} at 0 and 3 T with (c) $I_p = 16$ mA and (d) $I_p = 12$ mA for a fresh sample. Comparison of ΔR_{xy} for a fresh sample and the same sample after 18 mA annealing at (e) $I_p = 16$ mA in a 3 T in-plane field ($\mathbf{H} \perp \mathbf{E2}$), (f) $I_p = 12$ mA at 3 T, (g) $I_p = 16$ mA at 0 T, and (h) $I_p = 12$ mA at 0 T.

Figure 4. (a) Pulse current dependence of ΔR_{xy} for a Pt(2 nm)/ α -Fe₂O₃(30 nm) bilayer when I_p is switched between E3 and E1 (10 pulses each) measured at 300 K. (b) Temperature dependence of ΔR_{xy} (between E3 and E1) at $I_p = 9$ mA. All measurements here are taken on a sample after 18 mA annealing. (c) ΔR_{xy} vs. I_p from (a), showing a linear dependence (red fitting line: $y = -0.0183 + 0.00243x$). (d) Semi-log plot of ΔR_{xy} vs. T for $I_p = 9$ mA from (b), indicating an exponential dependence. (e) In-plane field dependence of ΔR_{xy} with $\mathbf{H} \perp \mathbf{E3}$ [$\alpha = 30^\circ$, see Fig. 2(c)], which tends to align $\mathbf{n} \parallel \mathbf{E3}$. The field is ramped from 0 to 1 T (green), then back to 0 T (red), which corresponds to a first-quadrant full hysteresis loop. In a separate scan, H is ramped from 0 to 0.1 T (green), then back to 0 T (blue), corresponding to a minor hysteresis loop. (f) Monte-Carlo simulations of the full and minor hysteresis loops of the component of $\mathbf{n}$ along E3 (n_{E3}) as a function of the effective magnetic field due to SOT generated by a pulse current $I_p \parallel \mathbf{E3}$, which agrees with the experimental data in (e).

References:

1. L. Q. Liu, C. F. Pai, Y. Li, H. W. Tseng, D. C. Ralph and R. A. Buhrman, Spin-Torque Switching with the Giant Spin Hall Effect of Tantalum. *Science* **336**, 555 (2012).
2. L. Q. Liu, O. J. Lee, T. J. Gudmundsen, D. C. Ralph and R. A. Buhrman, Current-Induced Switching of Perpendicularly Magnetized Magnetic Layers Using Spin Torque from the Spin Hall Effect. *Phys. Rev. Lett.* **109**, 096602 (2012).
3. C. O. Avci, A. Quindeau, C. F. Pai, M. Mann, L. Caretta, A. S. Tang, M. C. Onbasli, C. A. Ross and G. S. D. Beach, Current-induced switching in a magnetic insulator. *Nat. Mater.* **16**, 309 (2017).
4. T. Kampfrath, A. Sell, G. Klatt, A. Pashkin, S. Mahrlein, T. Dekorsy, M. Wolf, M. Fiebig, A. Leitenstorfer and R. Huber, Coherent terahertz control of antiferromagnetic spin waves. *Nat. Photonics* **5**, 31 (2011).
5. X. Marti, I. Fina, C. Frontera, J. Liu, P. Wadley, Q. He, R. J. Paull, J. D. Clarkson, J. Kudrnovsky, I. Turek, J. Kunes, D. Yi, J. H. Chu, C. T. Nelson, L. You, E. Arenholz, S. Salahuddin, J. Fontcuberta, T. Jungwirth and R. Ramesh, Room-temperature antiferromagnetic memory resistor. *Nat. Mater.* **13**, 367 (2014).
6. J. Železný, P. Wadley, K. Olejník, A. Hoffmann and H. Ohno, Spin transport and spin torque in antiferromagnetic devices. *Nat. Phys.* **14**, 220-228 (2018).
7. V. Baltz, A. Manchon, M. Tsoi, T. Moriyama, T. Ono and Y. Tserkovnyak, Antiferromagnetic spintronics. *Rev. Mod. Phys.* **90**, 015005 (2018).
8. W. Zhang, M. B. Jungfleisch, W. J. Jiang, J. E. Pearson, A. Hoffmann, F. Freimuth and Y. Mokrousov, Spin Hall Effects in Metallic Antiferromagnets. *Phys. Rev. Lett.* **113**, 196602 (2014).
9. T. Jungwirth, X. Marti, P. Wadley and J. Wunderlich, Antiferromagnetic spintronics. *Nat. Nanotechnol.* **11**, 231 (2016).
10. S. Urazhdin and N. Anthony, Effect of polarized current on the magnetic state of an antiferromagnet. *Phys. Rev. Lett.* **99**, 046602 (2007).
11. R. Cheng, J. Xiao, Q. Niu and A. Brataas, Spin Pumping and Spin-Transfer Torques in Antiferromagnets. *Phys. Rev. Lett.* **113**, 057601 (2014).
12. T. Satoh, R. Iida, T. Higuchi, M. Fiebig and T. Shimura, Writing and reading of an arbitrary optical polarization state in an antiferromagnet. *Nat. Photonics* **9**, 25 (2015).
13. V. Lopez-Dominguez, H. Almasi and P. K. Amiri, Picosecond Electric-Field-Induced Switching of Antiferromagnets. *Phys. Rev. Appl.* **11**, 024019 (2019).
14. O. Gomonay, T. Jungwirth and J. Sinova, High Antiferromagnetic Domain Wall Velocity Induced by Neel Spin-Orbit Torques. *Phys. Rev. Lett.* **117**, 017202 (2016).
15. R. Cheng, D. Xiao and A. Brataas, Terahertz Antiferromagnetic Spin Hall Nano-Oscillator. *Phys. Rev. Lett.* **116**, 207603 (2016).
16. R. Zarzuela and Y. Tserkovnyak, Antiferromagnetic textures and dynamics on the surface of a heavy metal. *Phys. Rev. B* **95**, 180402 (2017).
17. H. V. Gomonay and V. M. Loktev, Spin transfer and current-induced switching in antiferromagnets. *Phys. Rev. B* **81**, 144427 (2010).
18. P. Wadley, B. Howells, J. Zelezny, C. Andrews, V. Hills, R. P. Campion, V. Novak, K. Olejník, F. Maccherozzi, S. S. Dhesi, S. Y. Martin, T. Wagner, J. Wunderlich, F. Freimuth, Y. Mokrousov, J. Kunes, J. S. Chauhan, M. J. Grzybowski, A. W. Rushforth, K. W. Edmonds, B. L. Gallagher and T. Jungwirth, Electrical switching of an antiferromagnet. *Science* **351**, 587 (2016).

19. M. Meinert, D. Graulich and T. Matalla-Wagner, Electrical Switching of Antiferromagnetic Mn_2Au and the Role of Thermal Activation. *Phys. Rev. Appl.* **9**, 064040 (2018).
20. X. F. Zhou, J. Zhang, F. Li, X. Z. Chen, G. Y. Shi, Y. Z. Tan, Y. D. Gu, M. S. Saleem, H. Q. Wu, F. Pan and C. Song, Strong Orientation-Dependent Spin-Orbit Torque in Thin Films of the Antiferromagnet Mn_2Au . *Phys. Rev. Appl.* **9**, 054028 (2018).
21. S. Y. Bodnar, L. Šmejkal, I. Turek, T. Jungwirth, O. Gomonay, J. Sinova, A. A. Sapozhnik, H. J. Elmers, M. Kläui and M. Jourdan, Writing and reading antiferromagnetic Mn_2Au by Néel spin-orbit torques and large anisotropic magnetoresistance. *Nat. Commun.* **9**, 348 (2018).
22. M. J. Grzybowski, P. Wadley, K. W. Edmonds, R. Beardsley, V. Hills, R. P. Campion, B. L. Gallagher, J. S. Chauhan, V. Novak, T. Jungwirth, F. Maccherozzi and S. S. Dhesi, Imaging Current-Induced Switching of Antiferromagnetic Domains in CuMnAs . *Phys. Rev. Lett.* **118**, 057701 (2017).
23. X. Z. Chen, R. Zarzuela, J. Zhang, C. Song, X. F. Zhou, G. Y. Shi, F. Li, H. A. Zhou, W. J. Jiang, F. Pan and Y. Tserkovnyak, Antidamping-Torque-Induced Switching in Biaxial Antiferromagnetic Insulators. *Phys. Rev. Lett.* **120**, 207204 (2018).
24. I. Gray, T. Moriyama, N. Sivadas, G. M. Stiehl, J. T. Heron, R. Need, B. J. Kirby, D. H. Low, K. C. Nowack, D. G. Schlom, D. C. Ralph, T. Ono and G. D. Fuchs, Spin Seebeck imaging of spin-torque switching in antiferromagnetic Pt/NiO heterostructures. *arXiv:1810.03997* (2018).
25. T. Moriyama, K. Oda, T. Ohkochi, M. Kimata and T. Ono, Spin torque control of antiferromagnetic moments in NiO . *Sci Rep* **8**, 14167 (2018).
26. L. Baldrati, O. Gomonay, A. Ross, M. Filianina, R. Lebrun, R. Ramos, C. Leveille, T. Forrest, F. Maccherozzi, E. Saitoh, J. Sinova and M. Kläui, Mechanism of Néel order switching in antiferromagnetic thin films revealed by magnetotransport and direct imaging. *arXiv:1810.11326* (2018).
27. B. Peters, A. Alfonsov, C. G. F. Blum, S. J. Hageman, P. M. Woodward, S. Wurmehl, B. Büchner and F. Y. Yang, Epitaxial films of Heusler compound $\text{Co}_2\text{FeAl}_{0.5}\text{Si}_{0.5}$ with high crystalline quality grown by off-axis sputtering. *Appl. Phys. Lett.* **103**, 162404 (2013).
28. A. J. Lee, J. T. Brangham, Y. Cheng, S. P. White, W. T. Ruane, B. D. Esser, D. W. McComb, P. C. Hammel and F. Y. Yang, Metallic Ferromagnetic Films with Magnetic Damping Under 1.4×10^{-3} . *Nat. Commun.* **8**, 234 (2017).
29. F. Y. Yang and P. C. Hammel, Topical review: FMR-Driven Spin Pumping in $\text{Y}_3\text{Fe}_5\text{O}_{12}$ -Based Structures. *J. Phys. D: Appl. Phys.* **51**, 253001 (2018).
30. Y. Cheng, S. S. Yu, A. S. Ahmed, M. L. Zhu, Y. Rao, M. Ghazisaeidi, J. Hwang and F. Y. Yang, Anisotropic magnetoresistance and nontrivial spin Hall magnetoresistance in $\text{Pt}/a\text{-Fe}_2\text{O}_3$ bilayers. *Phys. Rev. B* **100**, 220408 (2019).
31. Y. Cheng, S. S. Yu, M. L. Zhu, J. Hwang and F. Y. Yang, Evidence of the Topological Hall Effect in $\text{Pt}/\text{Antiferromagnetic Insulator}$ Bilayers. *Phys. Rev. Lett.* **123**, 237206 (2019).
32. F. P. Chmiel, N. Waterfield Price, R. D. Johnson, A. D. Lamirand, J. Schad, G. van der Laan, D. T. Harris, J. Irwin, M. S. Rzchowski, C. B. Eom and P. G. Radaelli, Observation of magnetic vortex pairs at room temperature in a planar $\alpha\text{-Fe}_2\text{O}_3/\text{Co}$ heterostructure. *Nat. Mater.* **17**, 581 (2018).
33. R. Lebrun, A. Ross, S. A. Bender, A. Qaiumzadeh, L. Baldrati, J. Cramer, A. Brataas, R. A. Duine and M. Kläui, Tunable long-distance spin transport in a crystalline antiferromagnetic iron oxide. *Nature* **561**, 222 (2018).

34. See Supplemental Material at [URL] for addition results of RHEED, SQUID, Monte Carlo simulation, and control measurements on Pt/Al₂O₃, Pt/SrTiO₃, and Pt/Cr₂O₃.
35. A. H. Morrish, *Canted Antiferromagnetism: Hematite*. (WORLD SCIENTIFIC, 1995).
36. T. Fujii, M. Takano, R. Kakano, Y. Isozumi and Y. Bando, Spin-flip anomalies in epitaxial α -Fe₂O₃ films by Mössbauer spectroscopy. *J. Magn. Magn. Mater.* **135**, 231-236 (1994).
37. S. Gota, M. Gautier-Soyer and M. Sacchi, Magnetic properties of Fe₂O₃(0001) thin layers studied by soft x-ray linear dichroism. *Phys. Rev. B* **64**, 224407 (2001).
38. L. Baldrati, O. Gomonay, A. Ross, M. Filianina, R. Lebrun, R. Ramos, C. Leveille, F. Fuhrmann, T. R. Forrest, F. Maccherozzi, S. Valencia, F. Kronast, E. Saitoh, J. Sinova and M. Kläui, Mechanism of Neel Order Switching in Antiferromagnetic Thin Films Revealed by Magnetotransport and Direct Imaging. *Phys. Rev. Lett.* **123**, 177201 (2019).
39. P. Chen, N. Lee, S. McGill, S. W. Cheong and J. L. Musfeldt, Magnetic-field-induced color change in α -Fe₂O₃ single crystals. *Phys. Rev. B* **85**, 174413 (2012).
40. L. Baldrati, A. Ross, T. Niizeki, C. Schneider, R. Ramos, J. Cramer, O. Gomonay, M. Filianina, T. Savchenko, D. Heinze, A. Kleibert, E. Saitoh, J. Sinova and M. Kläui, Full angular dependence of the spin Hall and ordinary magnetoresistance in epitaxial antiferromagnetic NiO(001)/Pt thin films. *Phys. Rev. B* **98**, 024422 (2018).
41. J. Fischer, O. Gomonay, R. Schlitz, K. Ganzhorn, N. Vlietstra, M. Althammer, H. Huebl, M. Opel, R. Gross, S. T. B. Goennenwein and S. Geprägs, Spin Hall magnetoresistance in antiferromagnet/heavy-metal heterostructures. *Phys. Rev. B* **97**, 014417 (2018).
42. C. C. Chiang, S. Y. Huang, D. Qu, P. H. Wu and C. L. Chien, Absence of Evidence of Electrical Switching of the Antiferromagnetic Neel Vector. *Phys. Rev. Lett.* **123**, 227203 (2019).

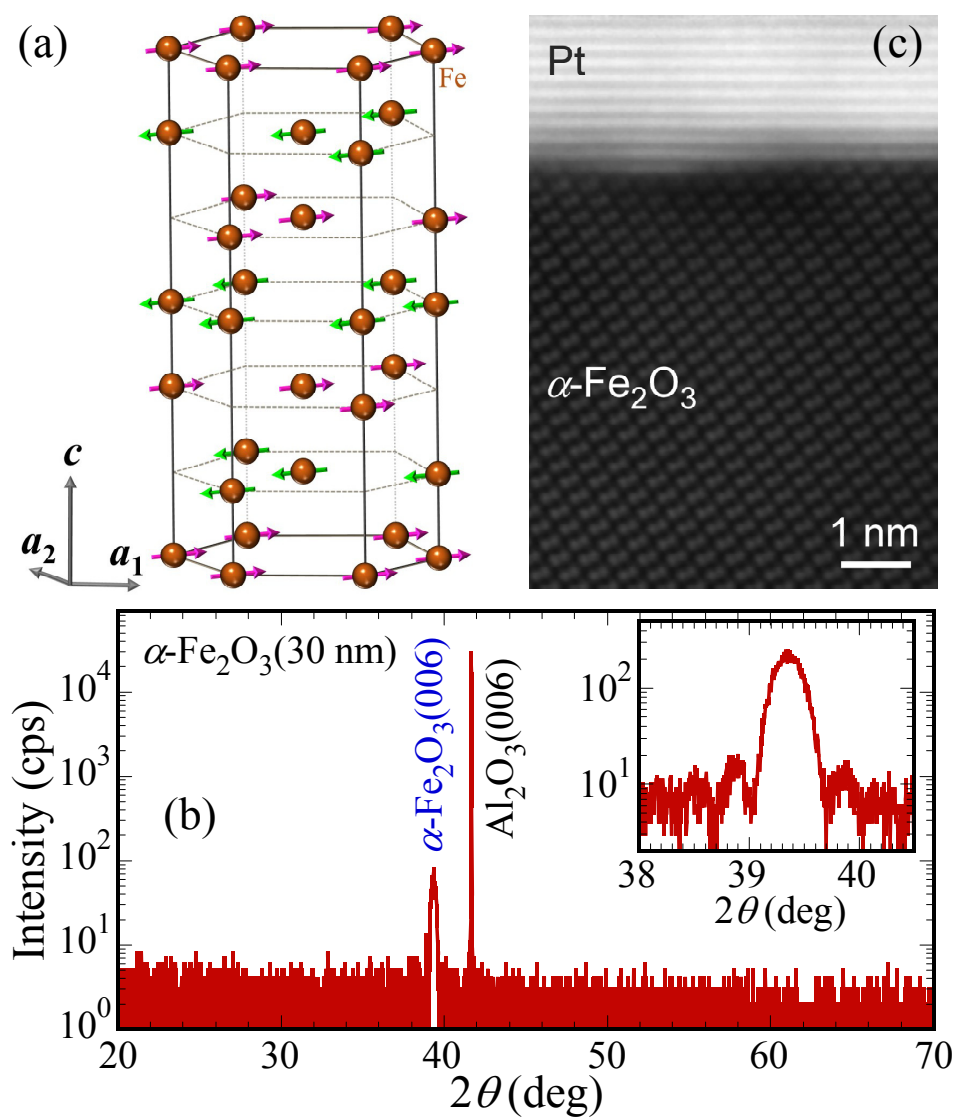


Figure 1.

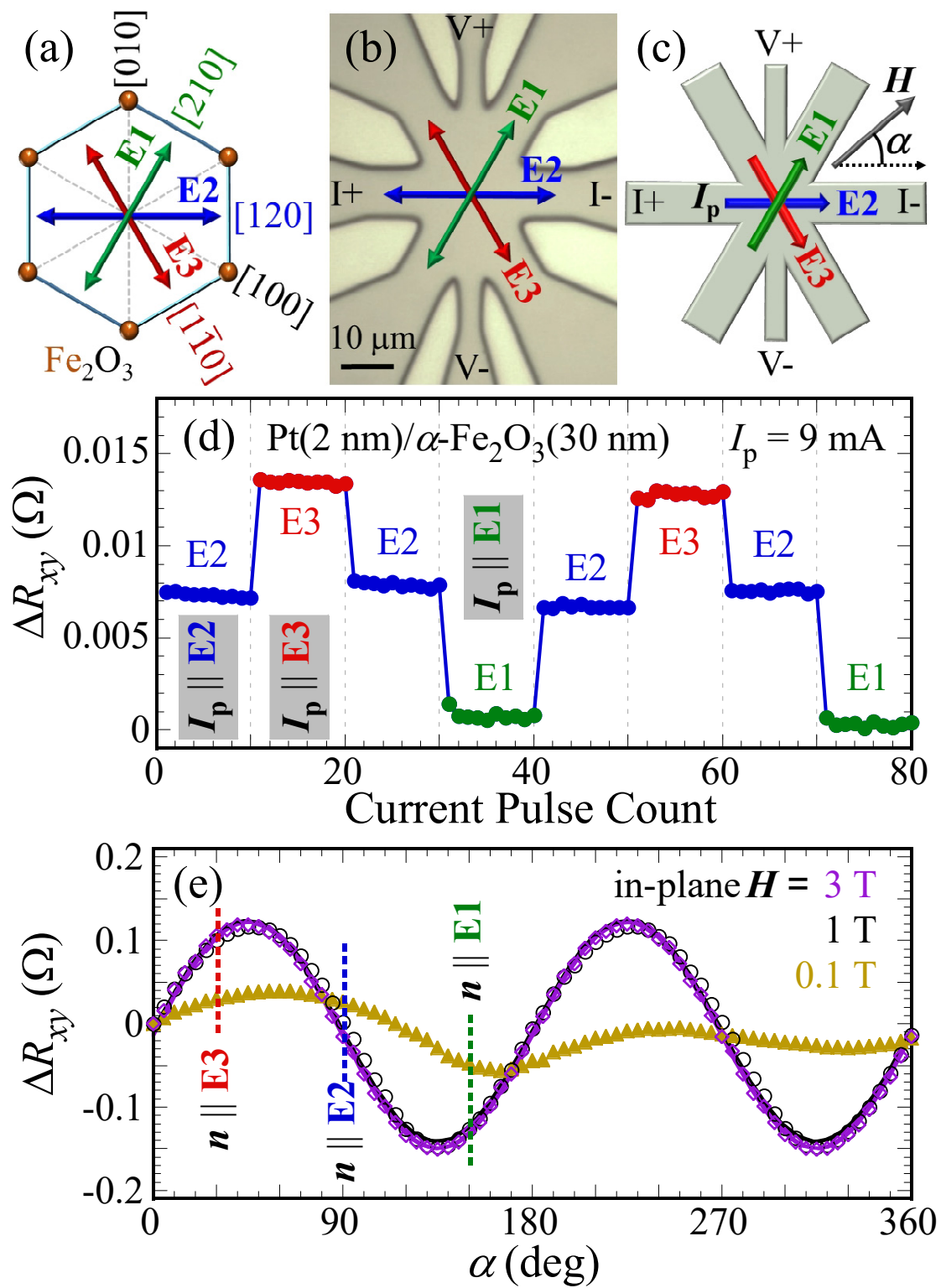


Figure 2.

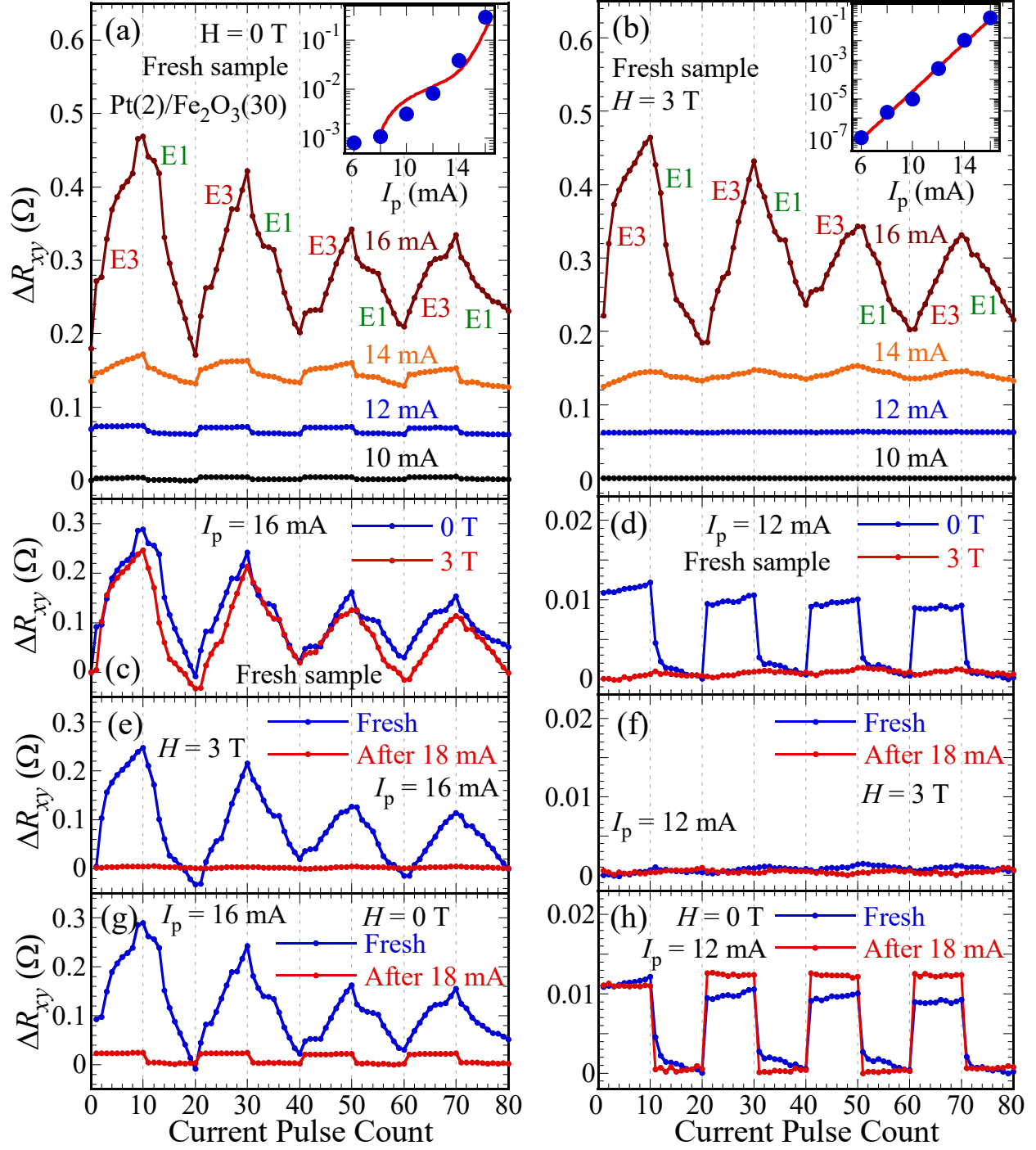


Figure 3.

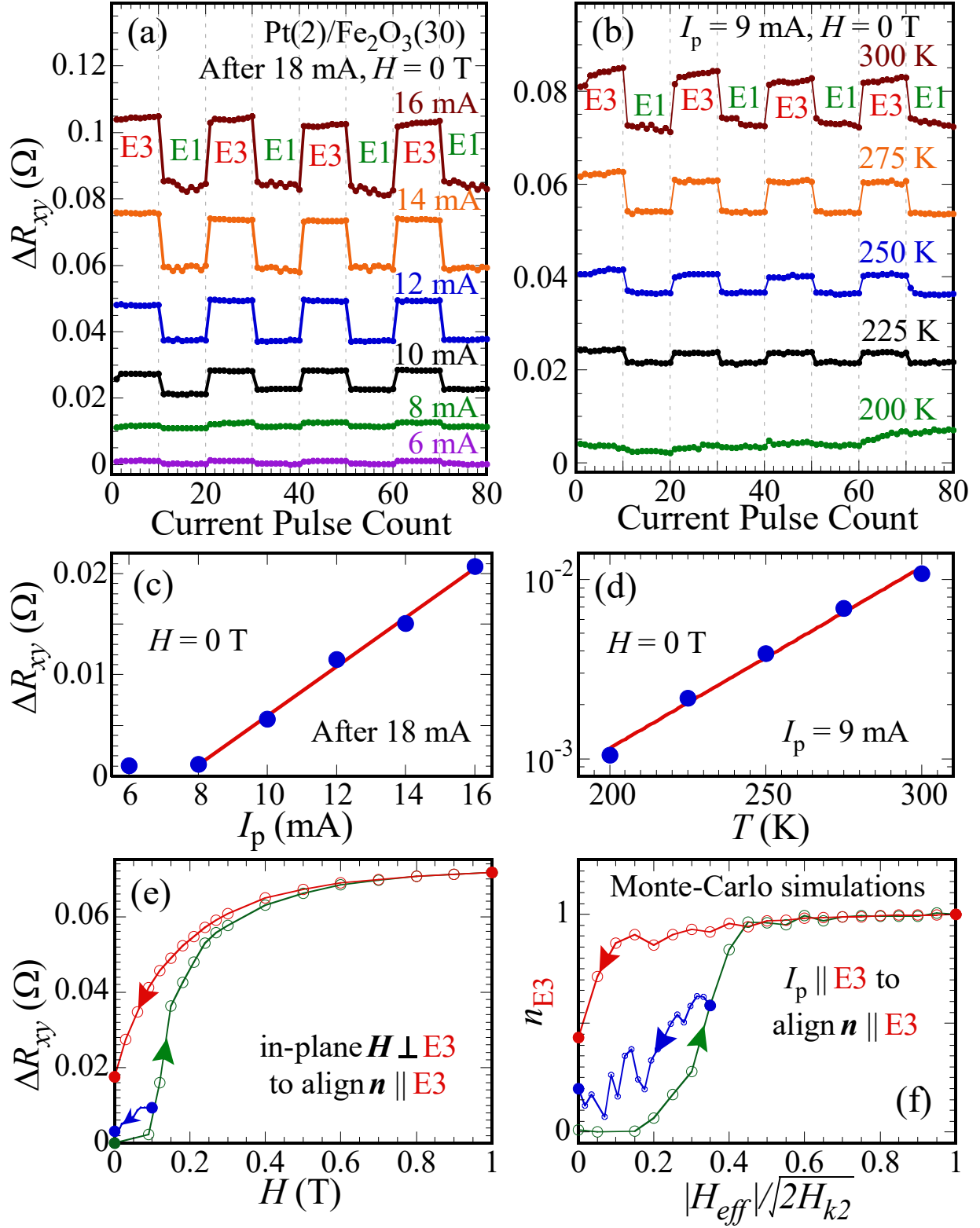


Figure 4.