Electrical manipulation of the magnetic order in antiferromagnetic PtMn pillars

Jiacheng Shi [1†], Victor Lopez-Dominguez [1†], Francesca Garesci [2], Chulin Wang [1],
Hamid Almasi [1], Matthew Grayson [1], Giovanni Finocchio [3*], Pedram Khalili Amiri [1*]

[1] Department of Electrical and Computer Engineering, Northwestern University, Evanston, Illinois 60208, United States of America

[2] Department of Engineering, University of Messina, Messina 98166, Italy

[3] Department of Mathematical and Computer Sciences, Physical Sciences and Earth Sciences, University of Messina, Messina 98166, Italy

[†] These authors contributed equally to this work.

[*] Corresponding authors: gfinocchio@unime.it , pedram@northwestern.edu

Abstract

Antiferromagnets are magnetically ordered materials without a macroscopic magnetization. As a result, they could be of use in the development of memory devices because data cannot be erased by external magnetic fields. However, this also makes it difficult to electrically control their magnetic order (Néel vector). Here we show that pillars of antiferromagnetic PtMn, which are grown on a heavy metal layer and have diameters down to 800 nm, can be reversibly switched between different magnetic states by electric currents. The devices are based on materials that are typically used in the magnetic memory industry, and we observe switching down to a current density of around 2 MA/cm^2. Furthermore, by varying the amplitude of the writing current, multi-level memory characteristics can be achieved. Micromagnetic simulations suggest that the different magnetic states may consist of domains separated by domain walls with vortex and anti-vortex textures that move in response to current, modifying the average Néel vector.

Antiferromagnetic (AFM) materials are promising for the development of spintronic device applications[1-8]. For example, due to their immunity to external fields, and intrinsic dynamics in the terahertz range[9], they could be used to create high-density memories with no inter-bit dipole interactions and fast write times. In addition, antiferromagnets have high resonance frequencies, which could potentially be useful for the development of compact room-temperature terahertz sources and detectors[10,11]. To implement these applications, however, efficient electrical control of the AFM order is required.

AFM order – expressed as the Néel vector – can be manipulated with strain[15,16], exchange bias[17,18], electric fields[19-22], and optically[12-14]. Recently, the manipulation of the Néel vector using electric currents has been explored in antiferromagnetic films with broken inversion symmetry (CuMnAs[7,23-25], Mn_2Au[26-30]), metallic MnN (ref. 31), and an insulator (NiO) interfaced with a large spin–orbit coupling material (Pt)[32-35]. The manipulation mechanisms investigated were the damping-like torque originating from the relativistic spin–orbit coupling in the AFM[7,23,25-27,30] (leading to current-induced spin polarization in the absence of equilibrium magnetization), and spin–orbit torque from the heavy metal[32-35]. In these experiments, writing current densities of 4 MA/cm^2 for CuMnAs (ref. 23), 10 MA/cm^2 for Mn_2Au (ref. 26), and 40 MA/cm^2 for NiO (ref. 33) were achieved. However, these studies focused on epitaxial films grown on lattice-matched substrates, and/or dielectric films, which are hard to integrate into memory devices with electrical readout[7,23,25-27,30,33]. To develop practical antiferromagnetic memories, material compatibility with silicon-based manufacturing will be required[36], as well as low switching currents for reliability and interfacing with scaled transistors, and a demonstration of memory operation in small patterned device structures.

In this Article, we report reversible electrical switching between different magnetic states in antiferromagnetic PtMn grown on a heavy metal layer. In particular, we investigate the electrical manipulation of the Néel order in circular PtMn pillars with diameters of 4–10 μm and thicknesses of 6–10 nm, using Pt/PtMn/MgO and Ta/PtMn/MgO structures. The materials used here (PtMn, Pt, and Ta) can be deposited by conventional sputtering at room temperature, and are already being used within the reference and metallization layers of magnetic tunnel junctions in magnetic random access memories, which semiconductor foundries integrate with state-of-the-art silicon technology[38].

We show switching of the AFM order between metastable states in our devices by applying a minimum switching current density of around 2 MA/cm^2. Micromagnetic simulations suggest that these metastable states may consist of non-uniform configurations with multiple vortex and anti-vortex structures. In contrast to previous studies on Néel vector manipulation in AFM films, we find that the switching mechanism is based on a damping-like spin–orbit torque originating from both the AFM and heavy metal layers, as well as a Zhang-Li torque[37], due to the spatial non-uniformities of the Néel order. Our experimental data also reveal that the readout signal is dependent on the last-largest current applied to the device. It could therefore potentially be possible to store more than one bit of information in a single memory element, or to store synaptic weights for neuromorphic computing applications.

Electrical manipulation of antiferromagnetic order

We first study devices based on Pt(5)/PtMn(6)/MgO(2.5) trilayers (thickness in nanometres) that are sputtered on a thermally oxidized silicon wafer (Fig. 1). The Pt layer acts as a source of spin current and the MgO is used as a protective capping layer. The Pt layer was patterned into a cross geometry with Au pads for multidirectional electrical measurements (Fig. 1a). The PtMn on top of the Pt layer was patterned into a circular pillar, with diameters ranging from 4 to 10 μm (see Fig. 1b, and Methods). Magnetic characterization using a vibrating sample magnetometer (VSM) in the field range between -1 and 1 T (see Supplementary Figure 1 and Supplementary Note 1) confirmed the AFM character of the PtMn films. It is worth noting that sputtered PtMn films can be ferromagnetic in some cases due to defects, especially when fabricated at high temperatures [39]. The VSM results, and the fact that the films of this study were deposited at room temperature, eliminate this possibility in our case. The manipulation of the AFM order is accomplished by bipolar current pulses (writing currents), applied along the device terminals B-B' (see Fig. 1b), i.e. the vertical leg of the device (see Methods). Readout is achieved by a second-harmonic detection technique, similar to that previously used for CuMnAs films [25], where an ac reading current with amplitude 0.5 mA and frequency 501 Hz is applied in the direction A-A' (perpendicular to the writing pulses). The second harmonic voltage response of the device is then measured along the B-B' direction, i.e. perpendicular to the ac probing current. Similar results were obtained by applying the current pulses in the horizontal leg (A-A') of the device and reading the second harmonic voltage along this same direction, while applying an ac reading current along B-B' (See Supplementary Note 2).

Figure 2 shows the second harmonic readout voltage, $V_{BB'}^{2\omega}$, as a function of time for a 4 μm pillar with PtMn thickness of 6 nm. The data are measured according to the writing protocol indicated in the inset of Fig. 2a. Each displayed value of the second-harmonic voltage is measured after one "write attempt", which consists of ten writing current pulses of 10 ms width. The polarity of the writing pulses is alternated in successive write attempts, while their amplitude is increased successively in 1 mA steps. The data clearly indicate the electrical manipulation of the AFM order in the PtMn pillar, with a bistable state that can be set by changing the current polarity with a given amplitude. It is interesting to note that, for the range of currents applied in these measurements, larger write current amplitudes result in larger second-harmonic voltage difference between the two states.

To investigate this voltage-current dependence in more depth, we performed a second set of measurements that monitor the second-harmonic voltage as the write current is varied. First, one writing current pulse of 10 mA was applied to set the initial state (point "I" in Fig. 2b). Then, we measured the minor voltage-current loops for writing currents swept back and forth between negative and positive values (i.e. -1 mA to 1 mA to -2 mA to 2 mA, etc.) up to 10 mA (point "II" in Fig. 2b). For each writing current pulse, the readout (second harmonic) voltage was then measured after the write current was set to zero. Figure 2b shows $V_{BB'}^{2\omega}$ as a function of current, measured with this protocol. The colour of each minor loop represents the maximum current used for its generation (see colour bar in Fig. 2b). Figure 2b also shows the voltage variation $\Delta V_{BB'}^{2\omega}$ between the states (i.e. plateaus) stabilized by -6 to +6 mA and -10 to 10 mA sweeps, respectively.

The gradual increase of $\Delta V_{BB'}^{2\omega}$ in successive loops indicates that the switching of the AFM order is taking place among different metastable states, identified by the plateaus in the minor loops. These states do not correspond to a complete rotation of the Néel vector, even in the case of 10 mA writing current (the maximum current that can be applied in these devices before electrical breakdown). In fact, in the case of uniform switching one would expect identical $\Delta V_{BB'}^{2\omega}$ values once the applied current overcomes a certain critical value. Additional measurements similar to those of Fig. 2 were carried out reducing the width of the pulse from 10 ms to 10 μs (for more information see Supplementary Note 4). The switching behaviour remained qualitatively the same over this range of pulse widths, but was accompanied by a reduction of the voltage variation as the pulse length decreased. This variation of the output voltage can be attributed to thermally activated depinning of the magnetic textures present in these samples, as well as to a deterioration of the pulse shape at the device due to parasitic effects from the low-frequency measurement pads.

The inset of Fig. 2b summarizes the readout voltage variation $\Delta V_{BB'}^{2\omega}$ as a function of the maximum applied current for different current loops. This plot indicates a memristive behaviour of these devices, where the readout voltage linearly depends on the maximum positive or minimum negative current previously applied to the device (see inset of Fig. 2a). The plot also reveals that the minimum current to observe a measurable $\Delta V_{BB'}^{2\omega}$ value is $I_C \sim 2$ mA, from which one can infer a switching current density J_C of the order of 2 MA/cm^2.

Micromagnetic modelling

We carried out micromagnetic simulations to better understand the spatial distribution of the Néel vector in the metastable states observed in our switching experiments (see Methods: Micromagnetic Simulations). Figure 3a shows a snapshot of a metastable state obtained for a 1 μm PtMn pillar. We chose a smaller diameter compared to the above experiments due to the excessive time required to simulate larger structures on our available computing resources. However, similar behaviour was also observed in sub-micrometer samples as discussed later in the text. The colour indicates the y-component of the Néel vector ($\boldsymbol{l_y}$), while the arrows indicate its in-plane direction. As seen from Fig. 3a, the Néel vector distribution is characterized by the presence of multiple vortex (V) and anti-vortex (AV) textures in the domain wall, stabilized by a trade-off between easy-plane anisotropy and exchange interactions [40]. We wish to highlight that these topological states have been observed in AFM films, such as hematite [41], NiO [33] and CoO [42]. Based on these calculations, we believe that the polarity-dependent switching observed in this work originates from the electrical manipulation of the domain walls and the change in the domain size (see discussion below and Supplementary Note 8). The second-harmonic output voltage thus results from a combination of the anisotropic and spin-Hall magnetoresistance

(AMR and SMR) effects, due to the resulting changes of the domain size in response to current. A physical mechanism at the basis of the electrical manipulation of the antiferromagnetic order in PtMn is the damping like-torque (DLT) originating from two sources: the relativistic spin–orbit torque proportional to the current flowing in the PtMn [43] (I_{AFM}) (referred to as the bulk DLT (b-DLT)), and the spin–orbit torque effect[44] that is due to the spin accumulation at the Pt/PtMn interface and is proportional to the current flowing in the Pt layer (I_{HM}) (referred to as interfacial DLT (i-DLT)). (Note that, given that the conductivities of PtMn and Pt are comparable [43] the current flows in both metals.) This scenario is different from previous switching experiments in CuMnAs [23], Mn_2Au [26] and NiO [33], where the Néel vector manipulation occurred only via b-DLT or i-DLT (since NiO is an insulator), respectively. In addition to these DLTs, we find that the Zhang-Li torque induced by I_{AFM}, originating from the non-uniform spatial distribution of the antiferromagnetic order, also plays a role in our devices [45] (see Supplementary Note 8 for a detailed discussion of the model). We next performed micromagnetic simulations of the current-induced motion of the V-AV patterns, including all of the above torque terms. For these simulations, we assumed the current density in the Pt (J_{HM}) and PtMn (J_{AFM}) to be the same, but no qualitative changes were observed when considering other ratios such as $J_{HM} = 0.8J_{AFM}$ or $J_{AFM} = 0.8J_{HM}$. The motion is reversible with current, as can be observed in Fig. 3b and Supplementary Video 1, which show the Néel vector dynamics driven by a 100 ps current of I = -20 mA, followed by one of the same length of I = 20 mA (see Supplementary Note 8 for details). In these simulations, we considered an initial state with a domain wall characterized by a single V-AV pair for simplicity. We therefore propose that the different Néel vector configurations, originating from the shifting of these domain walls, are the origin of the current dependence of the measured readout voltage.

Memristive characteristics

It is worth noting at this point that the initial point "I" and the final point "II" of the major loop in Fig. 2b do not coincide, i.e. they are not characterized by the same Néel vector configuration. Experimentally, this behaviour was observed only during the first measurement, in fact after performing repeated switching loop measurements from -10 mA to 10 mA and vice versa, the data showed that all subsequent loops were closed (See Supplementary Note 6, showing five consecutive loops measured in the same sample). We interpret this peculiarity of the first major loop as an initial transient where minor domains are removed from the pillar, with the remaining metastable states being robust and further stabilized by pinning potentials in the polycrystalline PtMn layer. Thus, after an initial current application of 10 mA, the writing procedure is robust and the resulting metastable states can be used as storage elements.

To investigate the reliability of switching between these metastable states, we also performed measurements considering as input a variable train of write current pulses, i.e. where the number of positive and negative write pulses were different. Figure 4 shows the results of this experiment. It can be seen that the final state is essentially independent of the number of times the writing pulse is applied with the same polarity. This shows a clear bistable characteristic for a fixed value of current, while a multi-level analogue (i.e. memristive) memory can be achieved as a function of the current amplitude (See Fig. 2b). This is in contrast with earlier experiments in CuMnAs [7], where the resistance value was dependent on the entire history of the applied current, and in particular, the application of an asymmetric number of current pulses with the same absolute amplitude resulted in a continuous increase of the resistance (compare Fig. 4 in this work with Fig. 2d in Ref. 7, where the multi-level sawtooth-like resistance pattern was attributed to domain wall motion in specific regions of the device [46]). This qualitative difference may be attributed to the presence of vortex and anti-vortex pairs, along with the reduced lateral dimensions of our device compared to earlier works, both giving rise to a different mechanism of stability and manipulation of the Néel order states.

The standard equation to describe memristive behaviour of a device is $V = M(x)I$, where V and I are voltage and current, while M represents its resistance that depends on a state variable x [47]. The state variable for antiferromagnetic memristive systems is the spatial distribution of the Néel vector that is manipulated by current, and whose time domain evolution is described by the LLG equations (see Supplementary Note 8). The unique feature of the devices studied in this work is that the output voltage does not depend on the whole history of the current, but only the last maximum or minimum value of the current pulse. This wiping-out property [48] is the key to enabling the linear memristive behaviour, depicted in the inset of Fig. 2b, which can open a new direction for AFM-based synapses in neuromorphic architectures. Finally, we note that memristive behaviour in magnetic systems is not confined to antiferromagnets and may also be observed in ferromagnetic spin-orbit torque devices [49,50].

Effect of film thickness and heavy metal selection

To better understand the relative contribution of the torques, we also studied the switching in Pt/PtMn devices with larger PtMn thickness, t_{PtMn} = 10 nm. Figure 5a shows the voltage-current loop (diameter of 4 μm) while Fig. 5d summarizes the voltage variation $\Delta V_{BB'}^{2\omega}$ as a function of the current. The results are qualitatively similar to those of t_{PtMn} = 6 nm, but now the contribution of the two torques is expected to be different. Namely, by increasing the PtMn thickness, i-DLT reduces for two reasons: It is inversely proportional to t_{PtMn}, while at the same time a larger amount of current is shunted in the PtMn, increasing both the b-DLT and the in-plane STT. In this context, it is interesting to compare the Pt/PtMn (6 nm) and Pt/PtMn (10 nm) curves in Fig. 5d. First, one can note slightly different $\Delta V_{BB'}^{2\omega}$ values for the largest measured currents. This could be a consequence of the different contributions of AMR and SMR in the magnetoresistive signal. However, for smaller currents (3 ~ 6 mA), the two curves are very similar, indicating a nearly equal critical switching current in both cases (i.e. the intercept with $\Delta V_{BB'}^{2\omega} = 0$ is approximately at 2 mA in both cases). This suggests that b-DLT together with the in-plane STT are very efficient for both samples, overcoming the reduced contribution of i-DLT in the thicker PtMn film. However, due to the non-uniform cross section of the device (i.e. having a circular conductive pillar) and the resulting non-uniformity of the current density distribution, we make no attempt at quantitatively comparing the critical switching current densities in the two cases.

To study the torques acting on the PtMn in further detail, we also constructed devices replacing the Pt layer with Ta, which has a higher resistivity and thus is expected to increase the portion of current passing directly through the PtMn pillar. The change from Pt to Ta increased the longitudinal resistance of our devices (i.e. measured along A-A' or B-B' in Fig. 1) from ~ 400 Ω to ~ 1.5 kΩ. In addition to the increased resistivity of the heavy metal, Ta is known to have a spin-Hall angle with opposite sign compared to Pt, hence changing the sign of the i-DLT contribution compared to the Pt-based devices. Figures 5b-c show the voltage-current loops for these Ta-based devices (all pillars having a diameter of 4 μm), while Fig. 5d summarizes the voltage variation $\Delta V_{BB'}^{2\omega}$ as a function of the current for all samples. The data are qualitatively similar to the devices built on top of Pt. The manipulation of the AFM order is characterized by a switching behaviour with the same polarity as in the Pt case, indicating that it is still dominated by the b-DLT and the in-plane STT terms. In addition, the memristive behaviour is also preserved. Interestingly, the Ta-based devices show somewhat smaller second-harmonic signals (also measured with a 0.5 mA reading current) for large write current values, a trend that is also observed in pillars with larger diameters (See Supplementary Note 7). However, the curves at lower currents are very similar, indicating that the overall write efficiency in both types of devices is similar. The increase of resistance due to the Ta heavy metal layer is also expected to increase the thermally-activated depinning effects compared to the Pt/PtMn based devices. This may be a contributing factor to explain the observed efficiency of switching in Ta/PtMn samples.

It is worth noting that qualitatively similar results were observed in an ensemble of 21 different devices, as shown in Supplementary Note 3. Our measurements under temperatures from 100 K to 400 K showed a similar switching behaviour across the entire temperature range. Reducing temperature slightly increased the readout signal, which might be attributed to reduced thermal perturbation and increased magnetoresistance effects (see Supplementary Note 5). In addition, to investigate the robustness of the AFM memory device against external magnetic fields, we subjected it to a field of 16 T. As shown in Supplementary Note 5, the switching behaviour of the device was essentially the same before and after the application of the field.

To study the scalability of the devices, we constructed sub-micrometer devices with the film structure Pt(5)/PtMn(6)/MgO. They were patterned in a cross structure for multidirectional electrical measurements and the PtMn was patterned in the middle of the cross, in a pillar shape of 800 nm diameter. The experimental steps performed for this structure were the same as the ones described before for larger devices, and the results are shown in Fig. 6. It can be observed that the switching and memristive behaviours are still present for this 800 nm device.

Conclusions

We have demonstrated reversible electrical control of the AFM order of PtMn pillars (with diameters down to 800 nm) in Pt/PtMn/MgO and Ta/PtMn/MgO structures. The AFM order can be switched with a minimum current of 2 mA, due to the combination of the SOT from the heavy metal (Pt or Ta), the intrinsic SOT present in the PtMn, and the in-plane torque of the antiferromagnetic texture. Furthermore, we have observed that the metastable states are dependent on the maximum current applied through the device, which suggests memristive characteristics. Notably, the AFM and heavy metal materials used in our devices are compatible with foundry processes for magnetic random access memory chips. Our results illustrate the potential of silicon-compatible antiferromagnetic materials for memory and computing devices, with potential advantages in terms of density, scalability, write energy, and operating speed.

Achieving practical AFM devices will require a number of further steps. First, it will be necessary to further scale down the device size. This will possibly change the underlying mechanisms of switching, because sufficiently small pillars will eventually exhibit single-domain behaviour. A relevant length scale for this transition may be the grain size of the material, which has been reported to be around 10-15 nm for sputtered PtMn films[51]. At the same time, it will be important to improve the read-out mechanism (possibly by using tunnelling anisotropic magnetoresistance[52] or other mechanisms to provide higher readout voltages) for use in both conventional memories and in unconventional (neuromorphic, for example) computing approaches. Finally, additional work is needed to experimentally confirm the detailed structure of the domain walls, the precise role of the thermal activation for the changes in the Néel vector, and the possible role of thermal annealing on the device characteristics.

Methods

Materials and sample fabrication. The materials used in this study were deposited on thermally oxidized silicon substrates, using sputter deposition under an Ar pressure of 2.5 mTorr at room temperature, in a physical vapour deposition system with base pressure less than 1×10^{-8} Torr. The PtMn films were deposited using DC sputtering from a $Pt_{50}Mn_{50}$ target. All samples were capped with 2.5 nm MgO to protect the AFM layer. The four structures, i.e. Pt (5) / PtMn (10), Pt (5) / PtMn (6), Ta (5) / PtMn (10), Ta(5) / PtMn (6) (thickness in nanometers), were patterned into the four-terminal devices shown in Fig. 1, using photolithography (e-beam lithography for nanometer devices) and dry etching techniques. Finally, after etching of the heavy metal layer and the pillar, Cr (5)/Au (80) electrodes were evaporated by electron beam to form the electrical contacts of the device.

Magnetic characterization. A reference film of Pt(5)/PtMn(6)/MgO (thickness in nanometers) was magnetically characterized before patterning using a Vibrating Sample Magnetometer (VSM) measurement system from Lake Shore. The samples were characterized in the field range between -1 and 1 T.

Measurements. Second harmonic measurements were performed using a lock-in amplifier SR830 from Stanford Research Instruments. The probing ac-current was provided by the lock-in, applying a sinusoidal current of 0.5 mA amplitude at a frequency of 501 Hz. It is noteworthy that the experiments were performed by connecting the grounds of the experiment to the internal ground of the lock-in amplifier via a 10 Ω resistor internal to the lock-in. Consequently, part of the ac probing signal was shunted to the reading direction. However, control experiments replacing the 10 Ω resistor by a 10 kΩ resistor (also internal to the lock-in) to eliminate the shunting, showed qualitatively similar results, thus demonstrating a multidirectional sensing of the second-harmonic signal as expected from the multi-domain structure of the PtMn. The current pulses for writing were applied by a Keithley 6221 power supply. All the applied pulses had a temporal width of 10 ms. Unless otherwise noted, all measurements were carried out at room temperature and in the absence of external magnetic fields.

Micromagnetic simulations. The AFM state is modelled by two sublattice magnetizations ($\boldsymbol{m}_1$ and $\boldsymbol{m}_2$). Its equilibrium configuration has been computed by numerically solving two Landau-Lifshitz-Gilbert equations [37,53-55]

$$\begin{cases} \dfrac{d\boldsymbol{m}_1}{dt} = -\gamma_0 \boldsymbol{m}_1 \times \boldsymbol{H}_{eff,1} + \alpha \boldsymbol{m}_1 \times \dfrac{d\boldsymbol{m}_1}{dt} \\ \dfrac{d\boldsymbol{m}_2}{dt} = -\gamma_0 \boldsymbol{m}_2 \times \boldsymbol{H}_{eff,2} + \alpha \boldsymbol{m}_2 \times \dfrac{d\boldsymbol{m}_2}{dt} \end{cases} \tag{1}$$

where γ_0 is the gyromagnetic ratio and α the Gilbert damping parameter. $\boldsymbol{H}_{eff,1}$ and $\boldsymbol{H}_{eff,2}$ are the effective fields for the first and second sublattice respectively. They include the easy plane anisotropy, the demagnetizing term, and the exchange field that is given by two contributions

$$\begin{aligned} \boldsymbol{H}_{1,exch} &= \frac{2A_{11}}{\mu_0 M_s} \nabla^2 \boldsymbol{m}_1 + \frac{4A_0}{a^2 \mu_0 M_s} \boldsymbol{m}_2 \\ \boldsymbol{H}_{2,exch} &= \frac{2A_{11}}{\mu_0 M_s} \nabla^2 \boldsymbol{m}_2 + \frac{4A_0}{a^2 \mu_0 M_s} \boldsymbol{m}_1 \end{aligned} \tag{2}$$

a being the lattice constant. In Eq. (2), A_{11} =0.3×10^{-11} J/m is the inhomogeneous intra-lattice contribution, A_0 / a^2 =12×10^6 J/m^3 is the homogeneous inter-lattice contribution, and the lattice constant is $a = 0.35$ nm. The initial magnetization state is considered random and a residual of 10^{-9} is set to determine the equilibrium configuration of the Néel vector $\boldsymbol{l} = \frac{\boldsymbol{m}_1 - \boldsymbol{m}_2}{2}$. The other material parameters are saturation magnetization $M_s = 0.4$ MA/m [21], easy plane anisotropy constant $K_{ep} = 100$kJ/m^3, x-y being the easy plane. Qualitatively similar results were obtained for A_{11}=0.1×10^{-11} J/m, $M_s = 0.3 - 0.5$ MA/m and $K_{ep} = 200$kJ/m^3.

Data availability

The data that support the plots within this paper and other findings of this study are available from the corresponding authors upon reasonable request.

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Author contributions

J.S., V.L.D., H.A., G.F., and P.K.A. designed the devices. V.L.D., J.S., and H.A. deposited the materials. J.S. fabricated the devices. V.L.D., J.S., and C.W. performed the measurements. F.G. and G.F. performed the micromagnetic simulations. P.K.A., G.F., V.L.D., and J.S. wrote the manuscript with contributions from the other authors. All authors discussed the results, contributed to the data analysis, and commented on the manuscript. J.S. and V.L.D. contributed equally to this research. The study was performed under the supervision of P.K.A.

Financial and non-financial competing interests

The authors declare no financial or non-financial competing interests.

Figure captions

Fig. 1| Device structure. a, Optical image of Pt/PtMn/MgO device with a 4 μm pillar diameter. The electrical contacts (Au) to the device are seen in bright color, while the heavy metal (Pt) is seen underneath the device in dark blue. **b**, A sketch of the device including the read/write signal sources.

An ac reading current is applied along AA’, while the writing pulse current and second-harmonic voltage readout are applied/measured along BB’.

Fig. 2| Current-controlled switching measurements. a, Second harmonic voltage measured after write attempts in alternating directions. The absolute amplitude values of write current range from 2 mA to 10 mA. The writing protocol is shown in the inset. The orange and blue bars denote writing pulse currents along BB’ as shown in Fig. 1a, but in opposite directions. The long brown bars denote the ac reading voltage. **b**, Current loops obtained by the second measurement protocol described in the main text. The minor loops demonstrate the manipulation of the metastable states of the AFM. The inset shows the variation of the second harmonic signal as a function of the maximum current for each loop. To account for possible errors associated with the sensitivity of the measurement setup, we did five consecutive measurements for each data point shown, and the indicated error bars correspond to the standard deviation. The solid line is provided as a guide to the eye.

Fig. 3| Micromagnetic simulations. a, A snapshot of the Néel vector (color refers to the y-component l_y while the arrows indicate the in-plane direction) of a metastable state, considering an easy plane anisotropy k_{EP}=1x10^5 J/m^3, and inhomogeneous exchange constant A_{11}=0.3×10^{10} J/m. The acronyms 'V' and 'AV' denote vortex and anti-vortex respectively. Similar configurations were observed for a range of simulation parameters. **b**, Time evolution of the average Néel vector components (x in black and y in red) in response to a current composed of two pulses (100 ps each), with amplitudes of -20 mA and 20 mA, respectively. The insets are the main representative snapshots. The point P_1 is the initial state, the point P_2 is the Néel state after the end of the first current pulse, while P_3 is the final state. See also Supplementary Video 1 for the full simulated switching process.

Fig. 4| Switching experiment with asymmetric number of write pulses. The blue and red points both represent the readout voltage measured after 10 mA writing current pulses, but in opposite directions along BB’. The readout voltage shows no significant dependence on the number of pulses (*N*) of a given amplitude in each pulse train, i.e. the first current pulse essentially accomplishes the switching to a given metastable state.

Fig. 5| Switching results for different antiferromagnetic film thickness and heavy metal materials. Current loops for **a,** Pt(5)/PtMn(10), **b,** Ta(5)/PtMn(10), and **c**, Ta(5)/PtMn(6). **d**, Second harmonic voltage variation as a function of the maximum applied current pulse amplitude. To account for possible errors associated with the sensitivity of the measurement setup, we did five consecutive measurements for each data point shown, and the indicated error bars correspond to the standard deviation. The solid line is provided as a guide to the eye.

Fig. 6| Current-controlled switching measurements on nanometer-scale devices. a, Switching for a Pt(5)/PtMn(6)/MgO device of 800 nm diameter applying current pulses in both directions with amplitudes ranging from 2 to 10 mA. **b,** Voltage loop measured for the same 800 nm device. As in the case of the micrometer devices, the system switches through multiple states, presenting a memristive behaviour. Solid lines are provided as guides to the eye.