









Identifying switching of antiferromagnets by spin-orbit torques

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Antiferromagnets are promising candidates for ultrafast spintronic applications, leveraging current-induced spin-orbit torques. However, experimentally distinguishing between different switching mechanisms of the staggered magnetization (Néel vector) driven by current pulses remains a challenge. In an exemplary study of the collinear antiferromagnetic compound Mn_2Au , we demonstrate that slower thermomagnetoelastic effects predominantly govern switching over a wide parameter range. In the regime of short current pulses in the nanosecond range, however, we observe fully Néel spin-orbit torque driven switching. We show that this ultrafast mechanism enables the complete directional alignment of the Néel vector by current pulses in device structures.

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I. INTRODUCTION

Antiferromagnets (AFMs) have been proposed as a groundbreaking platform in spintronics, enabling information storage through the encoding of data in the alignment of the staggered magnetization, also termed the Néel vector [1–4]. The integration of antiferromagnets (AFMs) as active components in spintronic devices can offer significant advantages, such as stability against external magnetic fields requiring additional magnetic anisotropy [5]. In particular, the magnetic domain configuration of our samples is stable in magnetic fields up to 30 T [6]. Furthermore, the intrinsically fast terahertz (THz) dynamics of AFMs [7] enables the manipulation of magnetic order by THz pulses [8].

Most approaches to the information-writing process, specifically the realignment of the Néel vector, focus on leveraging current pulse-induced spin-orbit torques (SOTs), as this mechanism is anticipated to enable a potentially ultrafast operation. Rotation of the Néel vector is envisioned to be driven by a strong exchange torque, generated when the AFM sublattices are tilted out of their originally antiparallel alignment [2]. In principle, such spin-orbit torques (SOTs) can arise from interfaces between antiferromagnets (AFMs) and nonmagnetic heavy metals, as well as from the bulk of metallic AFMs with inversion symmetry breaking in their combined crystallographic and magnetic structure, a mechanism referred to as Néel spin-orbit torque (NSOT) [9–11].

However, experimental evidence for the contribution of NSOTs to current-induced Néel vector reorientation remains limited. These indications primarily consist of observations

of current-polarity-dependent motion in a small fraction of domain walls in CuMnAs [12,13] and Mn_2Au [14] and in a complex directional dependence of small domain modifications in NiO/Pt [15].

On the other hand, an alternative effect has been identified that also induces Néel vector reorientation in antiferromagnets, albeit at a much slower rate compared to SOT-driven processes. This thermomagnetoelastic mechanism arises from current-induced heating, which generates strain and modifies the magnetic anisotropy, ultimately leading to Néel vector reorientation [16,17]. Distinguishing between these two mechanisms is challenging, yet it is crucial to experimentally verify that current pulse-driven SOT can serve as an ultrafast switching mechanism in antiferromagnetic spintronics.

In principle, there is also a third mechanism to be considered, which is based on inhomogeneous current heating due to the anisotropic magnetoresistance (AMR) of AFM domains with different Néel vector orientation. Within this model, the domains with higher resistance, i.e., temperature, should be removed [18]. However, for the compound investigated here, this mechanism can be excluded, because the AMR of Mn_2Au results in a higher resistance for a perpendicular alignment of Néel vector and current [19], which is the final configuration after the switching discussed below.

In this study, we focus on tetragonal Mn_2Au [20], which shows collinear AFM ordering with four equivalent easy $\langle 110 \rangle$ directions. An NSOT was predicted for this exemplary compound [9]; however, it was also shown that its AFM domain configuration also can be modified by externally applied strain [21,22].

We investigate current pulse driven Néel vector switching in Mn_2Au and demonstrate that, for pulses of 10 μs or longer, the reorientation process is predominantly driven by the

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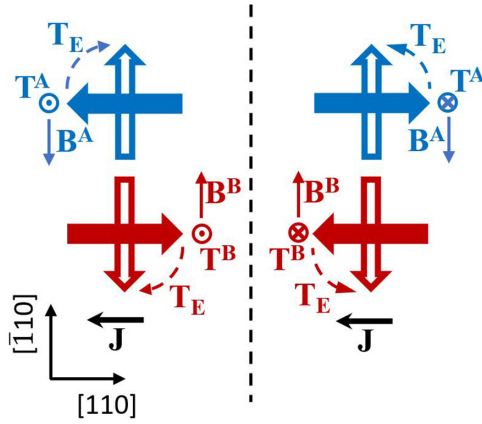


FIG. 1. Schematic representation of NSOT driven Néel vector switching. The initial configuration shows two antiparallel orientations of Néel vectors (180° domains) corresponding to swapped sublattice magnetizations $\mathbf{M}_{A/B}$ (filled arrows). The sublattice sites are connected by a crystallographic inversion. An NSOT driven by the current \mathbf{J} reorients the Néel vectors $\mathbf{N} = \frac{1}{2}(\mathbf{M}_A - \mathbf{M}_B)$ of both domains in the same direction indicated by the open arrows, thereby removing the 180° -domain wall indicated by the dashed line.

thermomagnetoelastic effect. In contrast, for pulses shorter than 100 ns, we observe switching of AFM domains driven purely by NSOT. Our conclusions are drawn from the analysis of the Néel vector orientation relative to the current direction, which, for a given geometry, exhibits distinct characteristics for the two mechanisms. Additionally, we demonstrate that an effective NSOT results in the alignment of the Néel vector along a specific direction, in contrast to the bidirectional alignment observed with a strain-induced easy axis.

II. RESULTS AND DISCUSSION

A. Direction of NSOT and thermomagnetoelastic Néel vector reorientation

In this section we will show how the choice of the sample geometry selects either a cooperation or a competition of the thermomagnetoelastic and of the NSOT switching mechanisms.

We consider a thin film geometry with a magnetic hard axis perpendicular to the sample plane. The direction of NSOT driven Néel vector reorientation is fully determined by the direction of the driving current \mathbf{J} . Following the derivation by Železný *et al.* [9], the staggered effective fields $\mathbf{B}^A = -\mathbf{B}^B$ at the AFM sublattices A and B are defined by the cross product of the normal \mathbf{z} on the easy thin film plane and the direction of the in-plane current \mathbf{J} (see Fig. 1):

$$\begin{aligned} \mathbf{B}^A &\propto +\mathbf{z} \times \mathbf{J}, \\ \mathbf{B}^B &\propto -\mathbf{z} \times \mathbf{J}. \end{aligned} \quad (1)$$

With this staggered effective field, the fieldlike torques \mathbf{T}^A and \mathbf{T}^B act for both AFM sublattices with antiparallel magnetizations $\mathbf{M}^A = -\mathbf{M}^B$ in the same direction, i.e., $\mathbf{T}^A = \mathbf{T}^B$:

$$\begin{aligned} \mathbf{T}^A &\propto \mathbf{M}^A \times (+\mathbf{z} \times \mathbf{J}), \\ \mathbf{T}^B &\propto -\mathbf{M}^A \times (-\mathbf{z} \times \mathbf{J}). \end{aligned} \quad (2)$$

The resulting canting of the sublattice magnetizations in the same direction out of the easy plane generates an exchange torque \mathbf{T}_E driven rotation of the Néel vector around \mathbf{z} , whose direction depends on the canting direction [2]. $\mathbf{T}^{A/B}$ is maximum for antiparallel/parallel alignment and zero for perpendicular alignment of the Néel vector to the current direction. If the magnetization directions of the AFM sublattices are swapped ($\mathbf{M}^{A/B} \rightarrow -\mathbf{M}^{A/B}$), corresponding to a sign change of the Néel vector, the torques change sign as well, as shown in Eq. (2). Thus, as visualized in Fig. 1, NSOT driven by a current parallel to the magnetic moments will reorient the Néel vector of 180° domains in the same direction perpendicular to the current.

Tetragonal Mn_2Au is characterized by a strong magnetic anisotropy with a hard c axis. The magnetic anisotropy within the (001) plane, which is much smaller, favors two mutually orthogonal magnetic easy axes along the $\langle 110 \rangle$ crystallographic directions. This results in a domain configuration of as grown epitaxial $\text{Mn}_2\text{Au}(001)$ thin film of sub- μm^2 sized domains with four $\langle 110 \rangle$ directions of the Néel vector [23]. Based on the discussion above, an NSOT arising from a current along the $[\bar{1}\bar{1}0]$ direction is expected to switch all domains with Néel vectors aligned parallel or antiparallel to this direction, not only perpendicular to the current but also into the same direction, such as the $[\bar{1}10]$ direction (Fig. 1). As no NSOT acts on the domains with Néel vectors aligned perpendicular to the current direction, those with Néel vectors pointing in the antiparallel $[\bar{1}\bar{1}0]$ direction are unaffected and 180° domain walls will persist. Thus, after a single current pulse through an ensemble of domains representing all four easy $\langle 110 \rangle$ directions, the Néel vector of all, but those with $[\bar{1}\bar{1}0]$ orientation, will point in the $[\bar{1}10]$ direction perpendicular to the current. However, these remaining domain walls are expected to be eliminated by a second current pulse now applied along the $[\bar{1}10]$ direction (which is perpendicular to the direction of the first pulse), as the NSOT will again rotate the antiparallel Néel vectors in opposite directions around the thin film normal by 90° . Thus NSOT is characterized by the complete alignment of the Néel vector, resulting in the formation of one large AFM domain within the active area of a switching device.

In contrast, the thermomagnetoelastic mechanism results in the formation of one axis, along which the Néel vector aligns both parallel and antiparallel, i.e., it favors the formation of 180° domains. Thermomagnetoelastic switching arises from current-induced heating and the resulting anisotropic thermal expansion of patterned thin-film samples clamped to thick insulating substrates. This can be illustrated by considering a thin, patterned metallic stripe heated by a current pulse. The normal thermal expansion of the stripe, associated with its temperature increase, is constrained by its clamping to the substrate, resulting in strain. However, this constraint is stronger in the direction parallel to the stripe than in the perpendicular direction, leading to compressive strain along the stripe. Thus the magnetic anisotropy is modified, driving a reorientation of the Néel vector. The axis of thermomagnetoelastic Néel vector alignment depends on the specific device geometry, as demonstrated below through simulations. Consequently, it can be either parallel or perpendicular to the current direction, depending on the sample geometry, which serves as

a clear criterion for distinguishing it from NSOT-driven Néel vector reorientation.

The direction of the strain resulting from a current pulse along a specific crystallographic direction can be varied by selecting an appropriate sample geometry. This means that the axis along which the thermomagnetoelastic effect aligns the Néel vector is adjustable, in contrast to the case of the NSOT mechanism, which always aligns the Néel vector perpendicular to the current direction. The typical geometry for current induced Néel vector switching is cross shaped. As shown in Fig. 2, this cross can be oriented with its arms parallel to the easy $\langle 110 \rangle$ axes (0° cross) or parallel to the in-plane hard $\langle 100 \rangle$ axes (45° cross). In both cases, the current direction in the center of the cross is selected to be parallel to the $[1\bar{1}0]$ direction as shown by the COMSOL [24] simulations in panels (a) and (d) of Fig. 2. The simulated spatially dependent temperature distribution at the end of a current pulse with a width of $10 \mu\text{s}$ is shown in panels (b) and (e). The corresponding spatial distributions of the strain, i.e., the relative difference in expansion between the $[1\bar{1}0]$ and the $[110]$ directions, are shown in panels (c) and (f). Please note that the sign of the strain is different for the two geometries, i.e., the centers of the crosses are strained (elongated) for the 0° cross perpendicular and for the 45° cross parallel to the current direction. This is related to the rotated orientation of the heated zones in the two geometries. Furthermore, the absolute value of the current heating induced strain is about a factor of five smaller for the 45° cross geometry. The magnitude of the strain generally decreases with decreasing pulse widths and current density (see also Sec. IV of the Supplemental Material and Refs. [25–28] therein).

The materials parameters required for the simulations (heat capacity, thermal conductivity, thermal expansion coefficient, Young's modulus, and Poisson ratio) are unknown for Mn_2Au . Thus typical values for metals were chosen. For details, see Supplemental Material, Sec. IV.

B. Imaging the switched domain configuration

We now present the corresponding experimental results, obtained by investigating patterned epitaxial $\text{Mn}_2\text{Au}(001)$ thin films using x-ray magnetic linear dichroism–photoelectron emission microscopy (XMLD-PEEM; see Methods). The XMLD signal, measured at the Mn- $L_{2,3}$ edge, ideally produces a black-and-white contrast for the perpendicular $\langle 110 \rangle$ axes along which the Néel vector is aligned. However, due to a small but unavoidable small energy dispersion of the photon beam over the illuminated sample area, the observed XMLD contrast exhibits spatial variation over the images.

The as-prepared AFM domain configuration of the epitaxial $\text{Mn}_2\text{Au}(001)$ thin films is discussed in detail in Ref. [29]; a typical example, featuring an equal population of sub- μm^2 sized domains, each with the Néel vector aligned along one of the four easy $\langle 110 \rangle$ directions, is presented in Fig. S1 of the Supplemental Material [30].

All switched samples shown here were initially pulsed along one of the easy $\langle 110 \rangle$ directions, followed by pulses along a perpendicular easy direction.

Figure 2, panels (g) to (j), display magnetic microscopy images of the AFM domain configuration obtained after applying current pulses with variable length in the configurations shown in panels (a) and (d). In the XMLD-PEEM setup, horizontal alignment of the Néel vector appears dark, while vertical alignment appears bright.

Current pulses with a duration of $10 \mu\text{s}$, applied along the same crystallographic $[1\bar{1}0]$ direction, result in a strong predominance of domains with the Néel vector aligned perpendicular to the current direction (bright) for the 0° cross configuration shown in panel (g). In contrast, for the 45° cross configuration shown in panel (h), the Néel vector orientation parallel to the current direction (dark) is dominant. This means that the same current pulse direction leads to mutually perpendicular alignment of the Néel vector in the center of the 0° and 45° crosses, corresponding to the perpendicular directions of the current-induced strain shown in panels (c) and (f). Thus these results provide strong evidence for the thermomagnetoelastic switching mechanism. Moreover, our experiments rule out NSOT as the driver of the reorientation process for pulse widths of $10 \mu\text{s}$ or longer (see also Supplemental Material, Fig. S2), as the direction of the NSOT depends solely on the current direction.

However, for current pulses with a length of 2.5 ns , both centers of the 0° and the 45° crosses shown in panels (i) and (j) display a strong predominance of Néel vector aligned perpendicular to the current direction by appearing bright in the XMLD-PEEM images. This result rules out the thermomagnetoelastic switching mechanism but is fully consistent with NSOT driven Néel vector reorientation.

Compelling evidence for NSOT-induced switching by nanosecond current pulses is provided by the observation of a predominantly single large domain in the center of the 45° cross, as shown in Fig. 2(j). This is because NSOT drives the Néel vector to align along a specific direction removing 180° domain walls. In contrast, after a $10 \mu\text{s}$ pulse, the center of the thermomagnetoelastically switched cross contains multiple closed loops of 180° -domain walls with a width close to the resolution limit in the XMLD-PEEM image as shown in Fig. 2(g) and discussed in more detail in Sec. II of the Supplemental Material.

To directly visualize the alignment of the Néel vector after the 2.5 ns pulses, we have additionally investigated 45° crosses of $\text{Mn}_2\text{Au}(40 \text{ nm})/\text{Ni}_{80}\text{Fe}_{20}(4 \text{ nm})$ bilayers. As described in Ref. [23], these bilayers exhibit a strong collinear exchange coupling between the Néel vector and the magnetization of the ferromagnetic $\text{Ni}_{80}\text{Fe}_{20}$. Consequently, externally driven rotations of either vector induce a coupled rotation of the other. By leveraging this coupling, we indirectly determine the direction of the Néel vector using XMCD-PEEM at the Fe edge, which reveals the orientation of the $\text{Ni}_{80}\text{Fe}_{20}$ magnetization [Fig. 3, panels (a) and (b)]. XMLD-PEEM at the Mn edge [panel (c)] confirms the assumed one-to-one correspondence between the AFM and FM domains also in the switched state.

These results highlight the unique capability of the NSOT to fully align the Néel vector and thereby to create a large single AFM domain from an initially multidomain state.

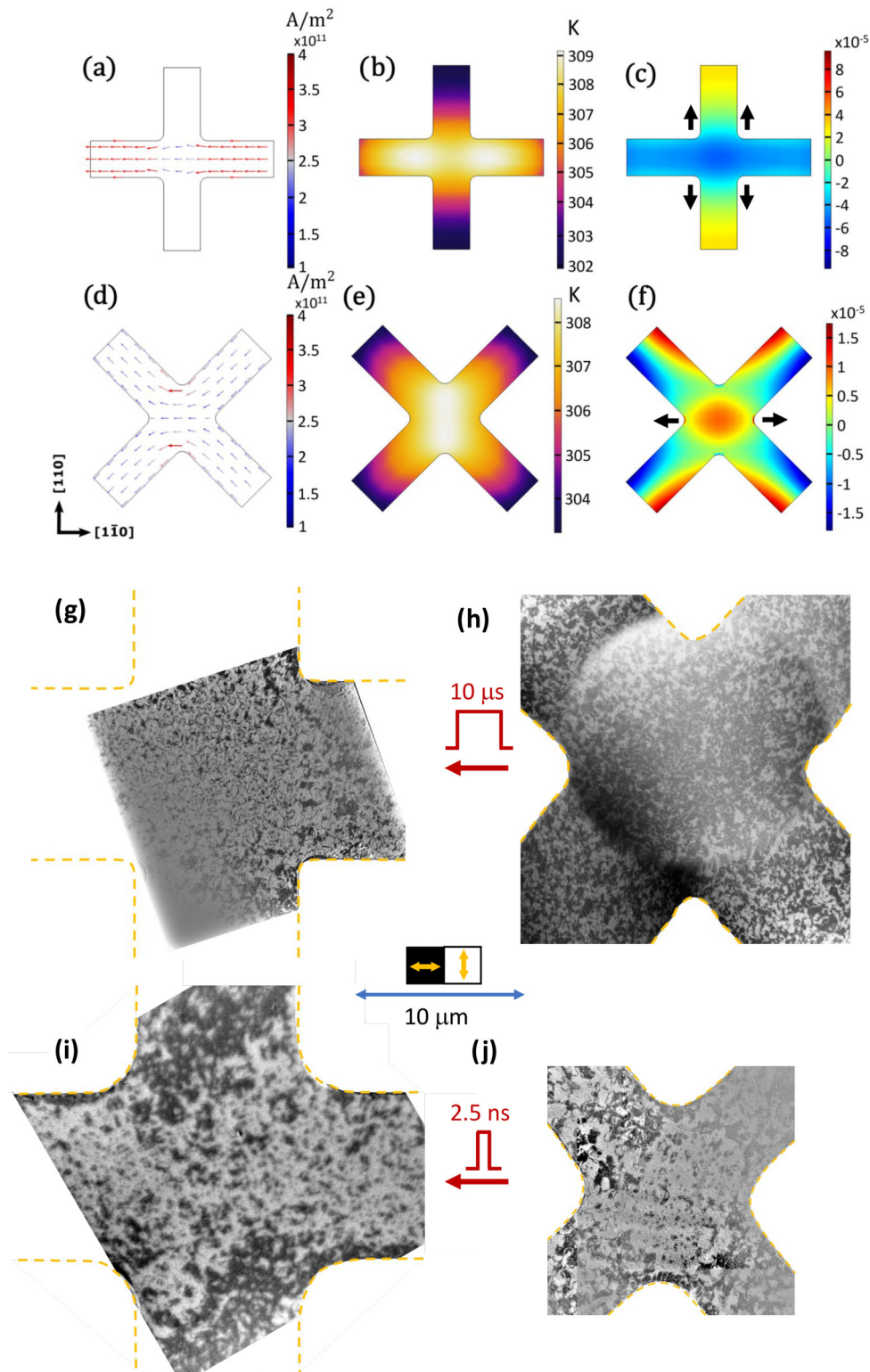


FIG. 2. Simulations and XMLD-PEEM images of current induced Néel vector reorientation. The top row [panels (a)–(c)] presents COMSOL [24] simulations for a 0° cross configuration. In panel (a), the current flows from the right arm to the left arm, panel (b) shows the associated temperature distribution after a $10\ \mu\text{s}$ pulse, and panel (c) depicts the resulting strain (black arrows indicate the direction of larger expansion), represented as the difference in relative expansion between the $[1\bar{1}0]$ and $[110]$ directions (see color bar). Panels (d)–(f) display the corresponding simulations for a cross rotated by 45° relative to the easy directions, where the current flows from both right arms to both left arms. Panels (g) and (h) (composed of five images) provide XMLD-PEEM images for experimental comparison of the two geometries after a $10\ \mu\text{s}$ pulse [(g) $3.3 \times 10^{11}\ \text{A/m}^2$; (h) $3.7 \times 10^{11}\ \text{A/m}^2$], while panels (i) and (j) show the corresponding images following a $2.5\ \text{ns}$ pulse [(i), (j) $2.5 \times 10^{12}\ \text{A/m}^2$]. The dimensions of the cross shown in panel (j) are reduced to enable larger current densities. Due to reduced experimental resolution, the 180° -domain walls appear blurred in panel (i).

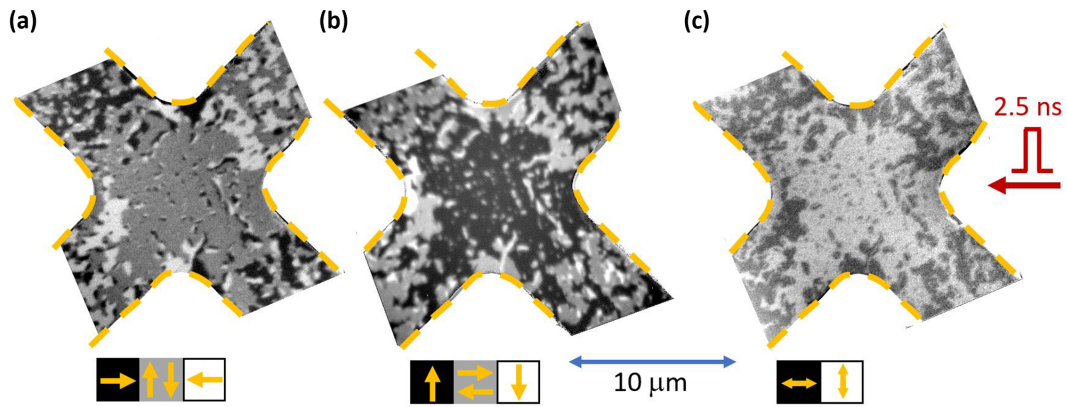


FIG. 3. XMCD- and XMLD-PEEM images of current induced Néel vector reorientation of $\text{Mn}_2\text{Au} / \text{Ni}_{80}\text{Fe}_{20}$. Panels (a) and (b) show the magnetization orientation of the $\text{Ni}_{80}\text{Fe}_{20}$ as obtained through XMCD-PEEM imaging at the Fe edge, with two different x-ray incidence directions. Panel (c) represents the corresponding XMLD-PEEM image at the Mn edge, captured after a 2.5 ns current pulse ($3.3 \times 10^{12} \text{ A/m}^2$), as indicated in the figure.

C. Electric characterization of switching

We employed both XMLD-PEEM imaging and anisotropic magnetoresistance measurements, associated with Néel vector reorientation, to identify the switched states (see Methods). Thermomagnetoelastic Néel vector reorientation was observed for current pulse durations of 1 ms (Supplemental Material, Fig. S2) and 10 μs [Fig. 2(h)]. In this regime, current pulses were applied *in situ* within the PEEM, enabling microscopic observation of changes in the AFM domain structure immediately after each pulse as the current density increased. Pulse widths in the range of 10 μs to 100 ns were applied outside the PEEM, as the sample stage wiring within the microscope does not support the impedance matching necessary for these shorter pulses. To precharacterize the switched state, we measured the transverse resistance of the samples prior to PEEM imaging. After each pulse application at progressively increasing current densities, the transverse resistance (planar Hall effect) was recorded. In these measurements, the increasing fraction of the switched area at the center of the cross-shaped devices is reflected as a corresponding increase or decrease in resistance. Once the resistance change saturates, the sample is considered fully switched and can be imaged *ex situ* using XMLD-PEEM.

Complete NSOT switching was observed at current densities ranging from $2 \times 10^{12} \text{ A/m}^2$ (100 ns pulses) to $3 \times 10^{12} \text{ A/m}^2$ (2.5 ns pulses) as shown in Fig. 4, panel (a). These values exceed by more than a factor of five the current density of $4 \times 10^{11} \text{ A/m}^2$ required for thermomagnetoelastic switching with 10 μs pulses. As the thermally generated strain induced by current pulses decreases with shorter pulse widths, thermomagnetoelastically driven switching eventually requires higher current densities than NSOT switching. Only in this crossover regime can switching driven by both mechanisms be observed at different current densities: for a pulse width of 100 ns, we observed NSOT switching at lower current densities, followed by thermomagnetoelastic switching at higher current densities, as indicated by the transverse resistance measurements in Fig. 4(a). For 100 ns pulse widths, the induced resistance changes initially follow the behavior observed for nanosecond pulses but subsequently reverse sign.

In this regime, saturation of the resistance change could not be achieved, as several samples failed under further increases in current density. However, the XMLD-PEEM image shown in Fig. 4(b), captured after completing the pulse sequence depicted in panel (a), clearly reveals a Néel vector alignment parallel to the current direction in the central region of the sample, consistent with expectations for thermomagnetoelastic switching.

III. METHODS

All experimental data shown in this manuscript were obtained investigating $\text{Mn}_2\text{Au}(001)(45 \text{ nm})$ thin films grown epitaxially on $\text{Ta}(001)(13 \text{ nm})/\text{Mo}(001)(20 \text{ nm})$ double buffer layers on $\text{MgO}(100)$ substrates. All layers were deposited by magnetron sputtering by the process described in detail in Ref. [31]. The samples were capped with 2 nm of polycrystalline SiN_x to protect them from oxidation. Optical lithography and ion beam etching were used to pattern the films into cross-shaped 50Ω matched coplanar wave guide structures as shown in the Supplemental Material (Fig. S4).

Antiferromagnetic domain imaging was performed by combining photoemission electron microscopy with x-ray magnetic linear dichroism (XMLD-PEEM) at the Mn $L_{2,3}$ absorption edge at the PEEM end stations at beamline MAX-PEEM at MAX IV and beamline I06 at Diamond Light Source and at the SIM beamline of the Swiss Light Source. The XMLD effect at the Mn $L_{2,3}$ absorption edge in Mn_2Au was established in previous work [23,32]. For x-ray polarization along a $\text{Mn}_2\text{Au} \langle 110 \rangle$ direction, the Mn $L_{2,3}$ XMLD spectrum shows a minimum and a maximum located at the absorption edge E_{max} and at 0.8 eV below the edge. At MAXPEEM, the x-ray beam has normal incidence at the sample surface. At I06 and SIM, the x-ray beam is incident at a grazing angle of 16° . The XMCD-PEEM images of $\text{Ni}_{80}\text{Fe}_{20}$ were obtained at I06 based on the x-ray magnetic circular dichroism at the Fe absorption edge.

In situ electrical manipulation was performed at MAX-PEEM using the pulse functions of a Keithley2601B-PULSE source for 10 μs and at SIM using Keithley 2430 (at Diamond)

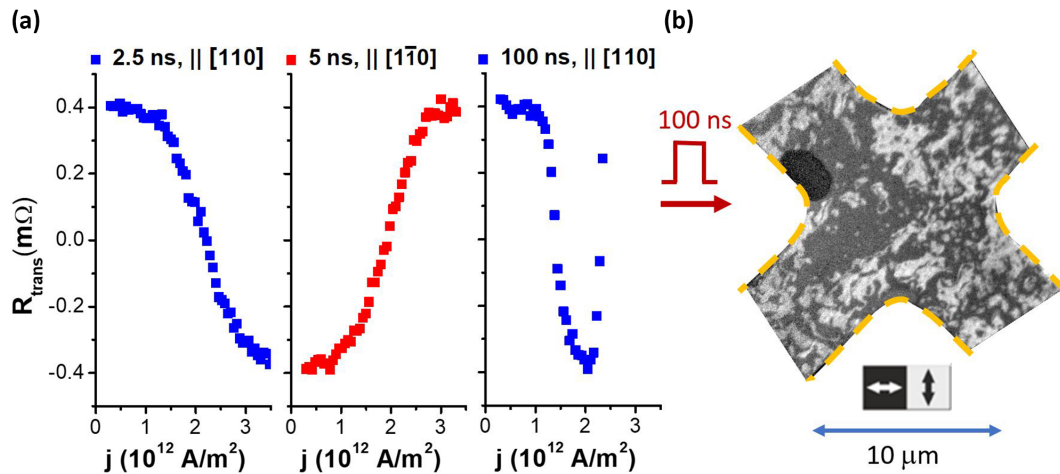


FIG. 4. Effect of Néel vector reorientation on the Mn_2Au resistance and reversed switching. Panel (a) shows the transverse resistance of a 45° Mn_2Au cross in response to sequences of current pulses along alternating perpendicular easy directions, with the pulse width indicated in the figure. After the final pulse sequence with a width of 100 ns, which resulted in a reversal of the resistance change, the sample was imaged using XMLD-PEEM, as shown in panel (b).

source meters for 1 ms pulses, integrated into the X-PEEM setup.

The *ex situ* pulsing in the 100 ns to 2.5 ns range was performed using a Siglent SDG7102A two-channel arbitrary waveform generator driving two Mini-Circuit LZY-22+ HF amplifiers. In this frequency range the required 50Ω impedance matching was obtained by using a coplanar waveguide design of the Mn_2Au thin films as shown in Fig. S4 of the Supplemental Material, by bonding the sample with short wire bonds onto a coplanar waveguide sample holder and by using exclusively coaxial cable connections.

The *ex situ* resistance measurements (Fig. 4) were performed using a Keithley 6220 precision current source with a probe current of $100\ \mu\text{A}$ and a Keithley 2182A Nanovoltmeter in Delta mode averaging over 100 measurements to obtain one data point. For automatising the pulse-probe sequence Teledyne CR33S30 HF-relais were used.

IV. SUMMARY AND CONCLUSION

In principle, all current pulse-induced magnetization switching in spintronics is associated with heating effects that generate strain. In epitaxial thin films, strain modifies the magnetocrystalline anisotropy of the investigated compound, ultimately leading to switching. Thus, when studying novel and potentially relatively weak switching mechanisms, such as SOTs acting on AFMs, it is essential to avoid confusion with the thermomagnetoelastic mechanism.

In the context of antiferromagnetic spintronics, the thermomagnetoelastic mechanism is inherently useful, as it in principle enables the switching of all collinear AFMs with multiple easy axes. However, its speed is limited because heat and strain must propagate across the active area of the devices. Thus achieving ultrafast processes necessitates SOT-driven dynamics.

The compound Mn_2Au is particularly noteworthy for its ability to exhibit both thermomagnetoelastic as well as NSOT switching within the same sample, facilitating their identification. We investigated Néel vector switching in two

distinct thin-film geometries, enabling a clear separation of the two mechanisms. Specifically, in the 45° -cross geometry, thermally induced strain and the predicted NSOT act in opposition. For current pulse widths in the millisecond and microsecond ranges, we observed a directional dependence of the Néel vector reorientation that is consistent with the thermal mechanism alone. However, a transition to NSOT switching is observed for pulse widths in the nanosecond range, as required for ultrafast applications. In this regime, the Néel vector aligns along a specific direction perpendicular to the current, which is a characteristic feature of the NSOT and could enable novel applications in spintronics.

Our experiments provide compelling evidence that the current-induced bulk NSOT, predicted 10 years ago [9], is sufficiently large to enable Néel vector switching in Mn_2Au devices. Therefore, despite the identification of often dominant thermomagnetoelastic switching, our results strongly support the fundamental viability of SOT-driven switching in AFM spintronics.

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The authors declare no competing financial interests.

DATA AVAILABILITY

The data that support the findings of this article are not publicly available. The data are available from the authors upon reasonable request.

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