

Electrical detection and control of synthetic antiferromagnets via perpendicular nanoscale magnetic tunnel junctions

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Detecting the magnetic states of synthetic antiferromagnets (SAFs) at the nanoscale is challenging due to their low net magnetization. We demonstrate an electrical method based on tunneling magnetoresistance (TMR) in nanoscale magnetic tunnel junctions to selectively detect the magnetization of a single SAF sublayer. TMR hysteresis loops reveal distinct switching behaviors governed by the competition between magnetic anisotropy and interlayer exchange coupling. This sensitivity enables direct quantification of exchange coupling under both field- and spin-transfer torque-driven reversals, while accessing the overall SAF magnetic state independent of its net magnetization.

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I. INTRODUCTION

Achieving fast and energy-efficient magnetization reversal while ensuring robustness against external perturbations is critical for advancing spintronic devices [1–6]. In this context, synthetic antiferromagnets (SAFs) have emerged as a promising candidate for enhancing device performance [7]. SAFs consist of two ferromagnetic layers coupled antiparallel via the Ruderman-Kittel-Kasuya-Yosida interaction through a nonmagnetic spacer [8]. Thanks to their tunable exchange interactions, SAFs improve device performance, including enhanced thermal stability and reduced stray fields [9]. Notably, SAF systems have been shown to enable efficient motion of magnetic textures such as domain walls and skyrmions thanks to the additional exchange coupling torque [10,11], and improve spin-orbit torque (SOT) switching efficiency [12–15]. These advantages establish SAFs as key materials for next-generation memory technologies [16–19]. Despite significant progress, detecting SAF magnetic states at the nanoscale remains a major challenge [20,21]. Conventional methods such as the magneto-optic Kerr effect

(MOKE) and vibrating sample magnetometry (VSM) measure only the net magnetization, with limited insights into individual layer dynamics. This is particularly problematic in nanoscale devices, where reduced volume and low net magnetization lead to weak magnetic signals. Advanced techniques like x-ray magnetic circular dichroism [22] and spin-LED spectroscopy [23] offer element-specific resolution but require complex instrumentation. The anomalous Hall effect offers an electrical probe, yet antiparallel SAF alignment suppresses its signal. A scalable electrical method to detect SAF magnetic states is therefore critical for both fundamental understanding and advancing SAF-based devices.

Here, we present an electrical method to detect SAF magnetic states by integrating Co/Ru/Co as the free layer of perpendicular magnetic tunnel junctions (MTJs). We demonstrate that tunneling magnetoresistance (TMR) provides layer-specific sensitivity of the SAF free layer, thus enabling the understanding of the SAF magnetization reversal, independent of the SAF's net magnetization. The resulting TMR hysteresis loops of the detected SAF sublayer reveal distinct switching behaviors governed by the competition between magnetic anisotropy and interlayer exchange coupling of the two sublayers. In the regime dominated by perpendicular magnetic anisotropy (PMA), the two sublayers switch sequentially, initiated by the sublayer with weaker anisotropy. Conversely, in the coupling-dominated regime, multistep TMR loops emerge, corresponding to simultaneous reversal of both SAF sublayers while maintaining their antiparallel alignment. Furthermore, reversals driven by field- and

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spin-transfer torque (STT) enable direct quantification of the exchange coupling field in nanoscale MTJs, a key parameter for evaluating SAF coupling strength. Overall, our findings establish a scalable electrical method to resolve layer-dependent switching in SAFs, offering new insights into their reversal mechanisms across different SAF configurations.

II. TMR DETECTION OF MAGNETIZATION SWITCHING IN SAFS

In our study, we integrated a Co/Ru/Co-based SAF with a CoFeB/MgO-based MTJ stack using a hybrid free layer design [24] [Fig. 1(a)]. Fabrication details are provided in Appendix A. The CoFeB layer is parallel coupled, via a W spacer, to one Co layer. This parallel coupling, confirmed by polar MOKE measurements presented in Note 1 in the Supplemental Material [25], allows the Co/W/CoFeB structure to be treated as a single magnetic layer, denoted M1. M1 is then coupled antiparallel to the second Co layer (M2) via a Ru spacer, so that M1 and M2 form the two SAF sublayers. While the CoFeB/MgO interface ensures optimal MTJ properties [26], the parallel coupling acts as a proxy to electrically detect a single SAF sublayer (M1), thereby assessing the SAF magnetic state.

We fabricated 100-nm-diameter MTJ pillars incorporating the SAF free layer. Figure 1(b) shows that although the total magnetization of the SAF, extracted from VSM measurements on blanket samples (Appendix B), varies with M1 Co thickness, the TMR ratio [Fig. 1(c)] remains unchanged, demonstrating that the TMR signal is primarily governed by the CoFeB/MgO interface and is independent of the SAF's net magnetization. Notably, TMR hysteresis loops exhibit pronounced dependence on the M1 Co thickness [Figs. 1(d), 1(e)].

During positive field sweeps (red curve), for both thin and thick M1 Co, an initial transition from the parallel (P , low resistance) to the antiparallel (AP , high resistance) MTJ state ($P \rightarrow AP$) indicates the reversal of the reference layer (RL, blue arrow), which is coupled antiparallel to a magnetic hard layer (HL) that remains fixed in the measured field range. The subsequent $AP \rightarrow P$ transition depends strongly on the M1 Co thickness. For a nominal thickness of 0.55 nm [Fig. 1(d)], the $AP \rightarrow P$ transition occurs before zero field, indicating that M1 reverses first to align antiparallel to M2. This switching field defines the SAF activation field $\mu_0 H_A$ and produces a counterclockwise hysteresis loop. Here, M2, stabilized by exchange coupling, reverses only during saturation. In contrast, for a nominal thickness of 0.65 nm [Fig. 1(e)], M1 reverses only at saturation, while M2 is expected to reverse earlier to establish the antiparallel alignment. The observed switching field corresponds to the SAF saturation field $\mu_0 H_S$, and the hysteresis loop becomes clockwise.

To better elucidate the SAF's switching process, Figs. 1(f) and 1(g) schematically illustrate the magnetization switching sequence during the field-driven TMR loops. Positive (red) and negative (blue) field sweeps highlight the distinct loop chirality: counterclockwise rotation corresponds to the SAF activation regime, whereas clockwise rotation corresponds to the SAF saturation regime. Solid arrows indicate the M1 reversals detected by the TMR, whereas dashed arrows correspond to undetected M2 reversals. Although not directly visible in the TMR signal, M2 switching is required for the observed M1 transitions, thus confirming that complete SAF reversal always involves both sublayers.

These switching behaviors differ fundamentally from those of conventional ferromagnetic free layers, where the $AP \rightarrow P$ transition always occurs at positive fields during

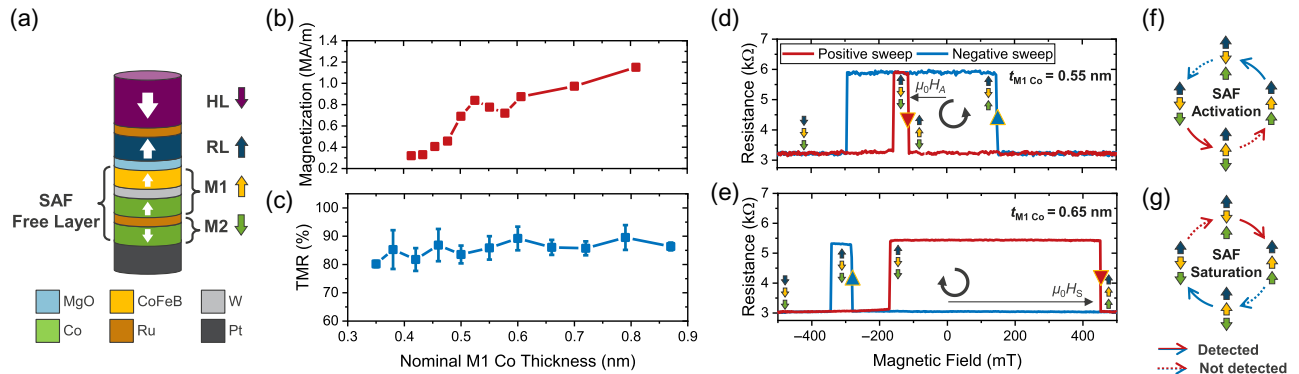


FIG. 1. (a) Schematic representation of the MTJ with SAF using hybrid free layer design. (b) Total SAF magnetization measured by VSM in blanket samples and (c) TMR ratio measured in 100-nm MTJs as a function of the nominal M1 Co thickness. While magnetization significantly varies with M1 Co thickness, TMR remains unchanged, demonstrating that the TMR detection, governed by the CoFeB/MgO interface, reflects the magnetic state of the SAF regardless of its net magnetization. TMR hysteresis loops for SAF-based MTJs with (d) 0.55 nm and (e) 0.65 nm nominal M1 Co thickness, revealing distinct SAF switching behaviors. (f) Schematic illustration of the switching sequence corresponding to the loop in (d), (g) to the loop in (e), emphasizing that TMR is sensitive only to M1 reversals. Dashed arrows mark M2 transitions, invisible in TMR.

a positive sweep, consistently producing clockwise loops. To understand the physical mechanisms of the different switching behaviors, we conducted micromagnetic simulations using MUMAX3 [27,28]. The simulations, presented in Appendix C, reveal that, during antiparallel alignment after saturation, the sublayer with lower PMA reverses first. Thus, the SAF switching sequence is dictated by the competition between the PMA of M1 and M2. Tailoring the PMA of each sublayer therefore enables tuning of the MTJ switching behavior, as further investigated in the next section.

III. PROBING MAGNETIC INTERPLAY IN SAF USING MTJ

This section explores how the relative PMA of SAF sublayers, tuned via M1 Co thickness, influences MTJ switching behavior, revealing the strong interplay between the SAF sublayers. We measured 100 field-driven TMR loops on 100-nm MTJ pillars with M1 Co thicknesses ranging from 0.35 to 0.9 nm, while fixing the M2 Co thickness at 0.8 nm. The results reveal three distinct TMR loops, as shown in Figs. 2(a)–2(c), with schematics summarizing

the switching sequences. To differentiate the switching behavior between these regimes, we recorded the $AP \rightarrow P$ switching field ($\mu_0 H_{AP \rightarrow P}$) as a function of nominal M1 Co thickness [Fig. 2(d)].

At very small M1 Co thicknesses, $\mu_0 H_{AP \rightarrow P}$ remains constant, suggesting that the M1 Co behaves as a magnetically dead layer, as confirmed by blanket measurements (Appendix B). In this case, SAF coupling is absent, and the TMR response reflects only CoFeB reversals. As the M1 Co thickness increases, $\mu_0 H_{AP \rightarrow P}$ becomes negative [red points, Fig. 2(d)]. The negative switching field corresponds to the SAF activation field, reflecting the counterclockwise hysteresis loop. This implies that M1 has lower PMA than M2, indicating an M2-dominated SAF configuration.

When the nominal M1 Co thickness exceeds 0.6 nm, $\mu_0 H_{AP \rightarrow P}$ becomes positive again (blue points), corresponding to the SAF saturation field. Here, M1 exhibits higher PMA than M2 (M1-dominated SAF), suggesting an inversion in PMA dominance. Interestingly, at the boundaries of the M2-dominated regime, $\mu_0 H_{AP \rightarrow P}$ fluctuates between positive and negative values, indicating that the transition between different regimes is gradual and

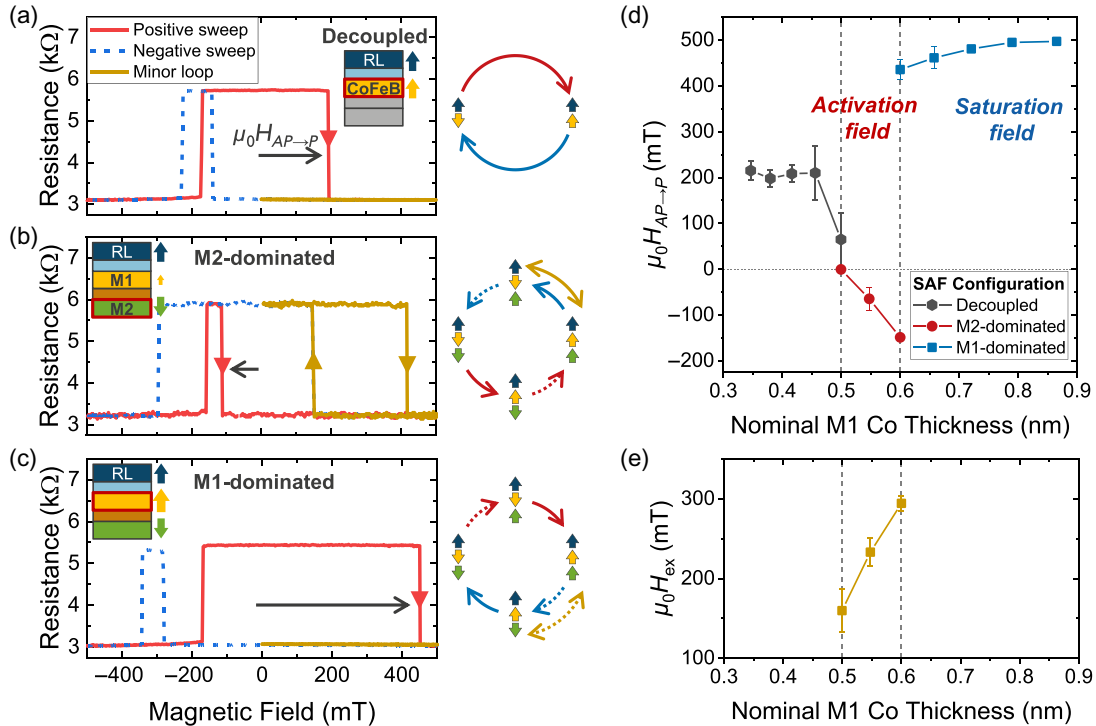


FIG. 2. Full and minor TMR loops detected in 100-nm MTJs with SAF free layers for (a) 0.45 nm, (b) 0.55 nm, and (c) 0.65 nm nominal M1 Co thickness. Black arrows indicate the $AP \rightarrow P$ switching field ($\mu_0 H_{AP \rightarrow P}$). The schematics illustrate the distinct SAF configurations and switching sequences depending on the nominal M1 Co thickness, with yellow arrows depicting the minor loop reversals. (d) $\mu_0 H_{AP \rightarrow P}$ as a function of nominal M1 Co thickness. In the M2-dominated regime, $\mu_0 H_{AP \rightarrow P}$ corresponds to the SAF activation field, while for the M1-dominated regime, it corresponds to the SAF saturation field. (e) Exchange coupling field ($\mu_0 H_{ex}$) derived from the offset of the minor TMR loops, increasing with M1 Co thickness and detectable only in M2-dominated SAFs.

thermal fluctuations play a crucial role in determining the switching behavior. In particular, at the 0.5-nm boundary, although the positive $\mu_0 H_{AP \rightarrow P}$ suggests a decoupled regime, its value is lower than that observed at slightly smaller M1 Co thickness. We anticipate that this behavior can arise from two scenarios: (i) the SAF remains effectively decoupled but the Co layer still has a weak PMA, lowering the effective anisotropy of the Co/W/CoFeB (M1) structure; or (ii) M1 exhibits a well-defined PMA but the antiparallel coupling to M2 is weak. In the latter case, the activation field, and thus $\mu_0 H_{AP \rightarrow P}$, can become slightly positive. Further explanation is provided in Appendix D, with square minor TMR loops (Note 3 in the Supplemental Material [25]) and VSM measurements (Appendix B) at this thickness favoring the second scenario and indicating weak antiparallel coupling rather than a still-decoupled state.

We now demonstrate that our approach allows direct measurement of the exchange coupling field ($\mu_0 H_{\text{ex}}$) using minor TMR loops, by sweeping the external magnetic field from zero to saturation and back. In the M2-dominated SAF configuration, M1 reverses before zero field, aligning antiparallel to a saturated M2. Reversing the field before reaching opposite saturation forces M1 to switch back, resulting in a shifted minor TMR loop [Fig. 2(b)]. This shift, of approximately 280 mT, corresponds to the sum of the exchange coupling field and offset field ($\mu_0 H_{\text{off}}$) generated by stray fields from the RL and HL. Symmetric behavior is observed for minor TMR loops at negative fields (Fig. S3 in the Supplemental Material [25]). The offset field can be measured from the shift of the full TMR loop, which is approximately 20 mT. Subtracting this offset from the minor TMR loop yields the exchange coupling field $\mu_0 H_{\text{ex}}$, whose dependence on M1 Co thickness is shown in Fig. 2(e). This trend closely matches VSM measurements in blanket samples, further validating our method.

Our results demonstrate that field-driven TMR detection identifies the dominant SAF sublayer and quantifies the exchange coupling field in nanoscale MTJs. Importantly, $\mu_0 H_{\text{ex}}$ can only be extracted in the M2-dominated SAF, where the activation field is visible via TMR response. As shown in the switching sequences of Fig. 2(c), in M1-dominated SAFs, the minor loop originates from M2 reversal, which is not detected in the TMR signal. In the next section, we address this limitation by employing a local STT-induced switching of M1.

IV. EXCHANGE COUPLING FIELD DETECTION VIA FIELD-ASSISTED STT

We introduce a complementary approach to extract $\mu_0 H_{\text{ex}}$ in M1-dominated SAF via switching induced by field-assisted STT (FASTT), illustrated in Fig. 3(a). In the absence of an external field, STT drives the local reversal

of M1, inducing an exchange torque on M2, switching the overall SAF state while preserving the antiparallel alignment (black arrows). An external field aligned with M2 counteracts this torque, hindering the M2 reversal. If this field exceeds a critical value, M2 reversal is suppressed, decoupling the sublayers. As a result, STT selectively switches M1 without reversing M2 (purple arrows), producing a change in the STT switching voltage. Interestingly, because this process directly involves M1, the detected sublayer, this transition becomes visible in M1-dominated SAF. We show that the threshold field corresponds to the SAF activation field, enabling the quantification of $\mu_0 H_{\text{ex}}$ where the field-driven method fails.

We investigated 100-nm MTJ SAF free layers with varying M1 Co thickness. Note that using STT introduces a challenge: while thicker M1 Co thickness promotes M1-dominated regimes, it also increases the switching voltage due to larger magnetic volume, raising the risk of device breakdown. To mitigate this, we inserted a 0.15-nm Pt layer between the M1 Co and Ru layers. This ultrathin insertion effectively tunes the M1 PMA without enlarging its volume [29], extending the M1-dominated SAF regime over a wide range of M1 Co thicknesses. This magnetic configuration is verified by field-driven TMR loops presented in Fig. S4 in the Supplemental Material [25].

To assess the FASTT method, we applied 100 STT voltage pulses of 50 ns with varying amplitude across the MTJs. Figure 3(b) shows the STT-driven TMR loop for a nominal M1 Co thickness of 0.6 nm. In presence of low external fields, the loop is nearly unchanged. However, above 90 mT, the $P \rightarrow AP$ switching voltage drops drastically. We quantified the switching voltage (V_{sw}), defined as half the width of the STT-driven TMR loop, across different M1 Co thicknesses [Fig. 3(c)]. For nominal thickness below 0.45 nm, the CoFeB layer is effectively decoupled and V_{sw} is not affected by the external field, but produces a rigid shift of the STT-driven TMR loop (Fig. S5 in the Supplemental Material [25]), consistent with conventional CoFeB/MgO-based MTJs [30]. In contrast, above 0.6 nm, where the antiparallel coupling is active, V_{sw} decreases at a specific field threshold, corresponding (as demonstrated below) to the SAF activation field. In this experiment, we observe that increasing M1 Co thickness leads to an increase in this field. For thicknesses exceeding 0.7 nm, this field surpasses our measurement capability.

To validate this method, we repeated the experiment on M2-dominated devices where the activation field is also detectable via a field-driven switching loop. The activation field values from both methods closely match (Fig. S5e in the Supplemental Material [25]), confirming FASTT as a reliable means of probing $\mu_0 H_{\text{ex}}$ in M1-dominated SAFs. By combining the activation field

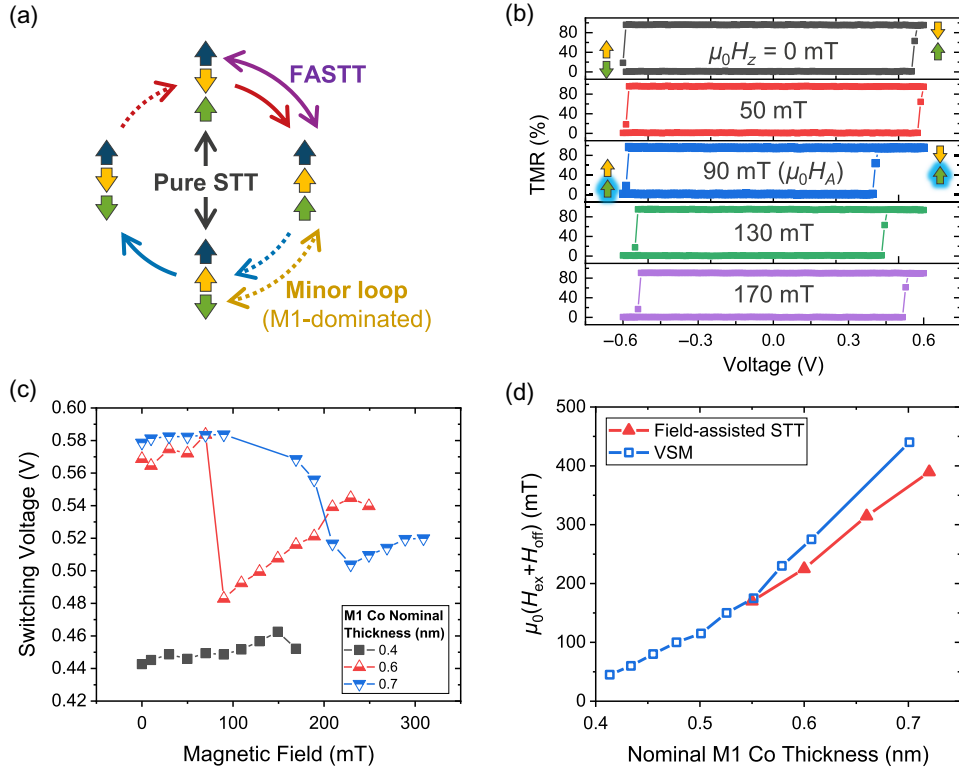


FIG. 3. (a) Schematic illustrating field-assisted STT (FASTT) approach where the external magnetic field counteracts the exchange coupling torque, decoupling the SAF while pinning M2. (b) Evolution of the STT-driven switching loop as a function of the external magnetic field in M1-dominated SAF free layer with M1 Co thickness of 0.6 nm. The reduced switching voltage indicates selective switching of the M1 layer, and the corresponding external field marks the SAF activation threshold. (c) Switching voltage dependence on the external magnetic field for M1-dominated configuration, in which the drop corresponds to the activation field. (d) Comparison of exchange coupling field plus field offset extracted from FASTT and from blanket VSM measurements, showing agreement between the two methods.

from FASTT ($\mu_0 H_A^{\text{FASTT}}$) with the saturation field from field-driven TMR loops ($\mu_0 H_S^{\text{TMR}}$, Fig. S4b in the Supplemental Material [25]), the exchange coupling field can be calculated as

$$H_{\text{ex}} = \frac{H_S^{\text{TMR}} + H_A^{\text{FASTT}}}{2} - H_{\text{off}}. \quad (1)$$

In this case also the MTJ offset field needs to be subtracted to extract the exchange coupling field. However, in our devices, the offset field of M1-dominated SAF cannot be extracted from the major TMR loop. The extraction of $\mu_0 H_{\text{off}}$ is only possible if the RL remains fixed during the switching of the SAF free layer. While this is true for the M2-dominated SAF devices, this condition is not fulfilled in M1-dominated devices, where the large negative SAF saturation field is larger than the RL switching field. Therefore, the $\mu_0 H_{\text{off}}$ contribution can no longer be separated. However, we expect $\mu_0 H_{\text{off}}$ to produce only a rigid shift of the extracted $\mu_0 H_{\text{ex}}$. Figure 3(d) compares the combination of $\mu_0 H_{\text{ex}}$ and $\mu_0 H_{\text{off}}$ values obtained from FASTT (red points) and VSM measurements on blanket samples

(blue dots, where the $\mu_0 H_{\text{off}}$ is negligible) as a function of M1 Co thickness. Both methods show a consistent increase of $\mu_0 H_{\text{ex}}$ with M1, confirming the validity of the FASTT approach also for M1-dominated configurations. The small discrepancy in absolute $\mu_0 H_{\text{ex}}$ values between the MTJs and blanket samples is attributed to $\mu_0 H_{\text{off}}$ of patterned MTJs and to the device geometry and fabrication process, which influence PMA and MTJ stray fields.

An intriguing behavior of V_{sw} emerges for external fields greater than the activation field. In this regime, only M1 switches under STT, which should resemble the behavior of very thin M1 Co cases, where V_{sw} (i.e., half of the STT-driven TMR loop) is unaffected by external field. Unexpectedly, however, we observe an increase in V_{sw} with field. This behavior reflects the interplay between external field and the exchange torque. Details are discussed in Note 6 in the Supplemental Material [25].

In summary, we have demonstrated that combining field- and STT-driven switching enables selective control of a single SAF sublayer. FASTT reveals the activation field even in M1-dominated regimes, overcoming limitations of field-driven approaches. Together, these

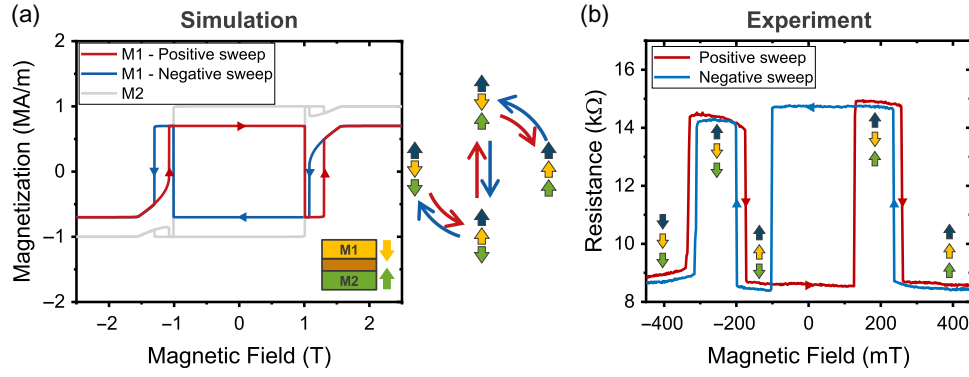


FIG. 4. (a) Micromagnetic simulations of SAF hysteresis with strong exchange coupling strength ($J_{\text{ex}} = -0.35 \text{ mJ/m}^2$), showing a three-step loop where the exchange coupling dominates over the PMA of SAF sublayers. The schematic illustration depicts the switching sequence highlighting the concurrent switching between antiparallel configurations. (b) Field-driven TMR hysteresis loop, displaying the three-step reversals of the M1 layer for both sweep directions.

results establish TMR readout as a scalable method to probe PMA competition and quantify exchange coupling in SAF-based MTJs. To obtain a complete picture of SAF switching behavior, we designed SAF-based MTJs where exchange coupling dominates PMA. This leads to a multistep TMR loop where both SAF sublayers switch simultaneously while maintaining antiparallel alignment, as presented in the next section.

V. TMR DETECTION IN EXCHANGE-DOMINATED SAFS

To investigate the impact of exchange coupling on SAF switching behavior, we performed micromagnetic simulations varying the exchange coupling constant J_{ex} while fixing the SAF sublayer magnetic properties. At higher coupling ($J_{\text{ex}} = -0.35 \text{ mJ/m}^2$), the hysteresis [Fig. 4(a)] shows a distinct three-step reversal in contrast to the two-step reversal at lower J_{ex} shown in Appendix C. This additional switching event, referred to as concurrent switching, arises when the exchange coupling dominates over the total PMA [22,23] of the SAF system, causing both sublayers to reverse simultaneously while maintaining antiparallel alignment. After saturation, the antiparallel alignment is initiated by the lower PMA sublayer (M1), followed by the three-step reversal, reflecting exchange-dominated dynamics. The schematic illustration in Fig. 4(a) depicts this switching sequence, including a transition between antiparallel states. Importantly, this behavior can be identified electrically via TMR readout.

Experimentally, unlike previous stack designs, we used a Co/Pt/Co multilayer for M2, incorporating a 0.3-nm Pt insertion layer to preserve PMA stability after 400 °C annealing (see Appendix A). This design enables direct observation of the concurrent switching via TMR, pointing to an exchange-dominated SAF free layer.

Following stack deposition, we fabricated MTJ devices with diameters ranging from 50 to 100 nm. Figure 4(b) shows a typical field-driven TMR loop of a 50-nm MTJ, revealing multistep switching behavior. This switching closely matches our simulation results for M1 layer switching [Fig. 4(a)]. Importantly, the same unconventional hysteresis is observed across different MTJ sizes (Fig. S7 in the Supplemental Material [25]), highlighting the robustness of the switching mechanism.

For positive field sweeps (red curve), the reference layer reversal is detected around -340 mT , followed by the activation field around -200 mT . As the magnetic field increases, the concurrent reversal appears around 120 mT . Finally, the saturation field is reached at approximately 250 mT . A fully symmetric switching loop occurs for a negative sweeping direction. Thus, the three-step TMR response directly reflects the switching of SAF sublayers under dominant interlayer exchange coupling. Importantly, in such exchange-dominated SAF, all switching events are detected by TMR signal and the M2 reversal is now captured during the concurrent switching.

Notably, in this case, the exchange coupling can be quantified from the offset field of the outermost hysteresis [22,23], extending our TMR-based approach to quantify H_{ex} applicable to all types of SAFs.

VI. CONCLUSIONS

We present a scalable electrical method to control and probe magnetization reversal in SAF-based perpendicular MTJs. TMR provides specific sublayer sensitivity, capturing SAF reversal dynamics governed by the interplay between PMA and interlayer exchange coupling: PMA-dominated SAFs show sequential reversal of the sublayers, while exchange-dominated SAFs exhibit simultaneous reversal while preserving antiparallel alignment. This approach enables quantitative extraction of the

exchange coupling field as well as precise characterization of SAF switching in nanoscale devices. These findings elucidate SAF magnetization dynamics and provide a framework for engineering nanoscale spintronic devices, including skyrmion- and domain wall-based SAF systems.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

APPENDIX A: METHODS

1. Sample preparation

The devices were fabricated on IMEC's 300-mm magnetoresistive random-access memory (MRAM) pilot line. First, Si/SiO₂ wafers were processed to embed W-VIAs employed as bottom electrodes. MTJ stacks were deposited on preprocessed wafers at room temperature by EC7800 Canon-Anelva magnetron sputtering systems under ultrahigh vacuum conditions and subsequently annealed at 300 °C for 30 min in the presence of an external magnetic field of 2 T. The 100-nm MTJ pillars were patterned by using 193-nm immersion lithography followed by ion-beam etching. Finally, a dual damascene Cu process was employed to top-contact the MTJ pillars. The SAF free layer stacks employed, according to the hybrid free layer design (SAF-HFL), in the field-driven and field-assisted STT switching experiments consist of (units in nanometers) Pt(5)/Co(0.8)/Ru(0.85)/Co(*t*)/W(0.3)/Co₂₀Fe₆₀B₂₀(0.8)/MgO(1) and Pt(5)/Co(0.8)/Ru(0.85)/Pt(0.15)/Co(*t*)/W(0.3)/Co₂₀Fe₆₀B₂₀(0.8)/MgO(1), respectively, where *t*

corresponds to the thickness of the M1 Co layer, which varied from 0.35 nm to 0.9 nm. The stack described in Appendix B consists of Pt(5)/Co(0.6)/W(0.3)/Co₂₀Fe₆₀B₂₀(0.8)/MgO(1). The reference and hard layer structure consists of a Co₂₀Fe₆₀B₃₀ layer, which is parallel coupled to an SAF consisting of Co(1.2)/Ru(0.85)/Co(0.6)/Pt(0.8)/[Co(0.3)/Pt(0.8)]₆. More information on the fabrication process is available in Ref. [24]. The MTJ pillar diameter in SOT-MRAM devices ranges from 50 nm to 100 nm, with the Pt track being 30 nm wider to ensure proper alignment during MTJ patterning.

2. Electrical measurements

To obtain the data shown in Figs. 2(d), 2(e), 12 devices were measured for each thickness by performing 500 TMR loops ranging from −500 mT to 500 mT for the full TMR loop and from 0 mT to 500 mT for the minor TMR loop approach. For Fig. 3(c), 100 STT switching loops were performed by sweeping the voltage pulse amplitude across the MTJs from −0.6 V to 0.6 V, using a fixed pulse width of 50 ns. For Fig. 4(f), 23 devices were tested for each MTJ size.

3. Micromagnetic simulations

Micromagnetic simulations were conducted using MUMAX3 to investigate the SAF field-driven hysteresis loop [27,28]. The SAF structure consists of two ferromagnetic layers, M1 and M2, separated by a nonmagnetic spacer. Both magnetic layers have a disk shape with a diameter of 100 nm and a thickness of 0.8 nm. The simulation discretization was set to 1 nm × 1 nm × 0.8 nm to ensure accurate modeling of the magnetic interactions. The antiferromagnetic coupling between the two layers was modeled using custom fields [28] using $B_{\text{ex}} = 2A_{\text{ex}}\mu_0 M_S \sum_{\langle i,j \rangle} (m_i - m_j)/c_{ij}^2$ with $A_{\text{ex}} = J_{\text{ex}} \times c$, where *c* corresponds to the cell size and *J_{ex}* represents the exchange coupling constant. The following material parameters were kept constant across all simulations: damping constant $\alpha = 0.1$, exchange stiffness $A = 16$ pJ/m, and Dzyaloshinskii-Moriya interaction constant $D = 0.01$ mJ/m². Two types of simulations were performed. First, the PMA interplay was analyzed by fixing the uniaxial anisotropy constant K_u and the saturation magnetization M_S of M2 at 900 kJ/m³ and 1000 kA/m, respectively, while varying K_u and M_S of M1 from 450 kJ/m³ to 900 kJ/m³ and from 700 kA/m to 1000 kA/m, respectively. The exchange coupling constant J_{ex} between M1 and M2 was maintained at −0.2 mJ/m². These simulations are discussed in Appendix C. Next, the high exchange coupling case was investigated by fixing the magnetic properties of M1 to $K_u = 475$ kJ/m³ and $M_S = 700$ kA/m, while keeping the properties of M2 unchanged. The exchange coupling constant J_{ex} was modified to −0.35 mJ/m² to study its impact on the hysteresis loop, as highlighted in the main text. For all simulations,

the external magnetic field was swept from -2 T to 2 T and back to -2 T, with a step size of 2 mT. This sweeping protocol enabled a comprehensive analysis of the hysteresis behavior of the SAF system under different parameter conditions.

APPENDIX B: MAGNETIC CHARACTERIZATION AND EXCHANGE COUPLING EVOLUTION IN BLANKET SAF-HFL

To quantify the total magnetic moments of the SAF-HFL system, VSM measurements were performed for various M1 Co thicknesses, as shown in Fig. 5. In this experiment, the RL and HL were replaced with a 3 -nm Ta capping layer to isolate the magnetic contributions only of the SAF-HFL. Figure 5(a) displays the hysteresis loops across different nominal M1 Co thicknesses. The magnetization of each magnetic layer was extracted by solving linear equations at two key points: the fully saturated state and the zero-field state, where the SAF sublayers are antiparallel aligned.

The extracted magnetization values are presented in Fig. 5(b). While the magnetizations of the CoFeB layer and the M2 layer remain constant, the magnetization of the M1 Co layer increases with the nominal thickness. Interestingly, below 0.45 nm, its magnetization is nearly zero, corresponding to the M1 Co dead layer thickness, while above 0.8 nm the magnetization saturates.

The VSM measurements also allow the extraction of the exchange coupling constant J_{ex} [31], derived by recording the exchange coupling field corresponding to the offset of the outer minor loops of the hysteresis loops. The results, shown in Fig. 5(c), reveal that J_{ex} increases in absolute value with M1 Co thickness, saturating at -0.8 mJ/m² for a nominal M1 Co thickness of 0.8 nm. This observation, together with the trend of the magnetization, confirms that the Ru/Co interface reaches uniformity at this thickness.

APPENDIX C: MICROMAGNETIC SIMULATIONS OF FIELD-DRIVEN SAF SWITCHING DYNAMICS

Micromagnetic simulations were conducted using MUMAX3 to investigate the interplay between the PMA of SAF sublayers. The simulation methods are reported in Appendix A. Figures 6(a) and 6(b) present the simulated hysteresis, showing the total SAF magnetization and the individual magnetization of the M1 and M2 sublayers for two different values of M1's anisotropy, with M_S of M1 fixed at 700 kA/m. M_S and K_u of M2 were fixed at 1000 kA/m and 900 kJ/m³, respectively. Given that only M1 is electrically detected in field-driven TMR loops, its simulated magnetization curves offer direct insight into experimental results. For $K_u = 500$ kJ/m³ [Fig. 6(a)] the total magnetization shows the typical two-step reversal of the SAF, where the M1 reverses before crossing zero field due to antiparallel coupling with M2 (SAF activation). In contrast, higher magnetic anisotropy ($K_u = 700$ kJ/m³) of M1 [Fig. 6(b)] results in the “butterfly”-shaped hysteresis. Here, M2 switches during SAF activation, and due to its higher M_S , the total magnetization changes sign. Importantly, M1 switches only during saturation of the SAF, that is, after crossing zero field at very large fields. In the two figures, schematic illustrations indicate the switching sequences, which align with those of Fig. 1 in the main text.

To systematically explore the switching behavior, we performed a comprehensive study shown in the diagram of Fig. 6(c). Each square corresponds to a simulation for varying K_u and M_S of M1. The magnetic parameters of M2 are highlighted by the top and rightmost square in the diagram. The colors denote the remanent magnetization of M1 after positive saturation. Blue regions indicate M1 reversal during SAF activation [analogous to Fig. 6(a)], while red regions indicate M1 reversal only after saturation [analogous to Fig. 6(b)]. To quantify the transition between the

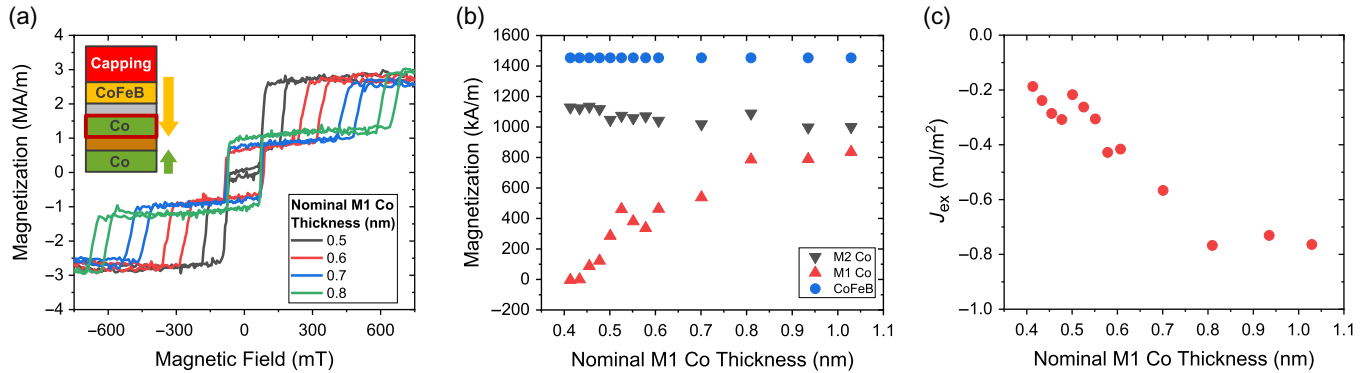


FIG. 5. (a) Hysteresis loops at different nominal M1 Co thicknesses of SAF hybrid free layer (HFL). (b) Extracted magnetization values of each SAF-HFL sublayer and (c) calculated exchange coupling constant J_{ex} for the measured nominal M1 Co thicknesses.

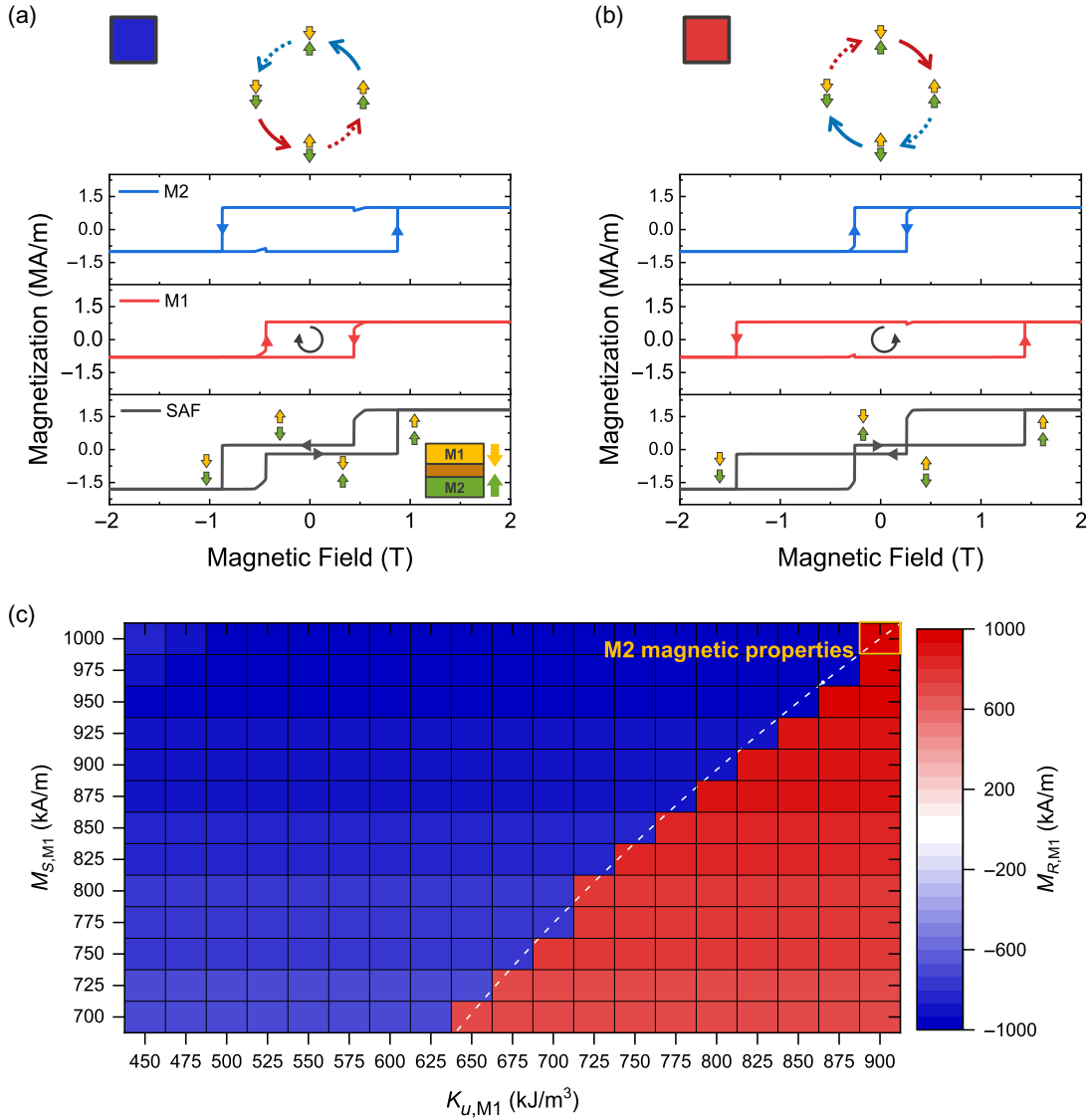


FIG. 6. Total magnetization of SAF and magnetization of the sublayers as a function of external magnetic field for magnetic anisotropy of M1 equal to (a) 500 kJ/m³ and (b) 700 kJ/m³, with saturation magnetization of M1 fixed to 700 kA/m. Schematic illustrations depict the switching sequences. (c) Simulation diagram for different combinations of saturation magnetization and magnetic anisotropy of M1 at fixed magnetic properties of M2 (highlighted by the top and rightmost, yellow-contoured square). The color of each square corresponds to the remanent magnetization of M1 after positive saturation. The dashed line represents the value of the saturation magnetization of M1 extracted from the analytical expression, corresponding to equating the SAF activation field due to the reversal of the two SAF sublayers.

two switching behaviors, we considered the total energy of the SAF system,

$$\begin{aligned}
 E_{\text{tot}} = & -K_{u,M1} (m_{M1} \cdot \hat{e}_z)^2 - K_{u,M2} (m_{M2} \cdot \hat{e}_z)^2 \\
 & + \frac{1}{2} \mu_0 M_{S,M1}^2 (m_{M1} \cdot \hat{e}_z)^2 + \frac{1}{2} \mu_0 M_{S,M2}^2 (m_{M2} \cdot \hat{e}_z)^2 \\
 & - \mu_0 M_{S,M1} H_Z \cdot m_{M1} - \mu_0 M_{S,M2} H_Z \cdot m_{M2} \\
 & + \frac{J_{\text{ex}}}{t} (m_{M1} \cdot m_{M2}), \quad (C1)
 \end{aligned}$$

from which the SAF activation fields corresponding to the reversal of either M1 or M2 were derived as

$$\mu_0 H_{A,M1} = \frac{E_{\text{eff},M1} + 2E_{\text{ex}}}{2M_{S,M1}} \quad (C2a)$$

$$\mu_0 H_{A,M2} = \frac{E_{\text{eff},M2} + 2E_{\text{ex}}}{2M_{S,M2}} \quad (C2b)$$

where $E_{\text{eff},i} = K_{u,i} - \frac{1}{2} \mu_0 M_{S,i}^2$ corresponds to the PMA energy of each SAF sublayer and $E_{\text{ex}} = J_{\text{ex}}/t$ to the exchange energy. By equating $\mu_0 H_{A,M1} = \mu_0 H_{A,M2}$, the

value of $M_{S,M1}$ can be extracted from the quadratic equation solutions

$$\mu_0 M_{S,M1} = -2\mu_0 H_{A,M2} \pm \sqrt{4(\mu_0 H_{A,M2})^2 + 2\mu_0 (K_{u,M1} + 2E_{ex})}. \quad (C3)$$

From this equation, only one solution is physically meaningful. The extracted $M_{S,M1}$ values are plotted as a dashed line in Fig. 6(c), marking the boundary between the two regimes. The sharp agreement between simulated and analytical results confirms the decisive role of PMA in SAF switching behavior, where the lower PMA SAF sublayer switches during antiparallel alignment before crossing zero field. In particular, the switching behavior of Fig. 6(a) corresponds to a lower PMA of M1 compared to M2 (M2-dominated SAF). This case corresponds experimentally to the switching behavior of Fig. 1(b) in the main text. Figure 6(b), instead, depicts the case of a higher PMA of M1 (M1-dominated SAF), corresponding experimentally to Fig. 1(c) in the main text.

APPENDIX D: PMA COMPETITION OF SAF SUBLAYERS AT REGIME TRANSITIONS

In Fig. 2(d), at the boundaries of the M2-dominated regime, we observe signatures of both positive and negative $\mu_0 H_{AP \rightarrow P}$, indicating that the transition between SAF configurations is not abrupt but influenced by thermal variations.

At nominal thickness of 0.5 nm two distinct TMR characteristics appear in the same device [Fig. 7(a)], corresponding to either decoupled or M2-dominated SAF signatures [Figs. 2(a) and 2(b), respectively]. Interestingly, in the decoupled case, the switching field is reduced compared to the values recorded for the same regime, but at

lower thicknesses. We believe that two possible scenarios can occur: first, the M1 Co layer starts to become magnetically active at this thickness, but with a still weak PMA. Because the M1 Co layer is coupled to the CoFeB layer through the W spacer, its reduced stability lowers the effective PMA of the combined Co/W/CoFeB stack (i.e., M1 SAF sublayer). This decrease in effective anisotropy would lead to a reduced switching field for the detected M1 layer. However, minor TMR loops at this thickness, reported in Fig. S3 in the Supplemental Material [25] suggest a stable PMA of the M1 layer. Alternatively, the PMA of the Co/W/CoFeB system may already be strong at this thickness, while the antiparallel coupling to the M2 Co layer is weak. In such case (strong PMA and weak coupling strength), as reported in literature [23], an SAF can still exhibit a two-step reversal sequence, but the SAF activation may occur only after crossing zero field. The resulting TMR loop of the M1 sublayer therefore resembles that of a decoupled layer, but with a lower switching field. This interpretation is supported by the square minor TMR loops observed at this thickness (Fig. S3 in the Supplemental Material [25]), which indicate a stable M1 layer, and by the low exchange coupling constant J_{ex} extracted from VSM measurements (Fig. 5), pointing to a weak antiparallel coupling. Overall, while both mechanisms could contribute to the reduced switching field, the second scenario appears the most consistent with the experimental observations.

At the thicker boundary (0.6 nm), the devices fluctuate between M2- and M1-dominated SAF configurations due to the nearly equal PMA of the two SAF sublayers. Such behavior also appears in the same device, suggesting the influence of thermal variations. The four different combinations of hysteresis loops and switching sequences, observed even for a single device over 500 cycles, are

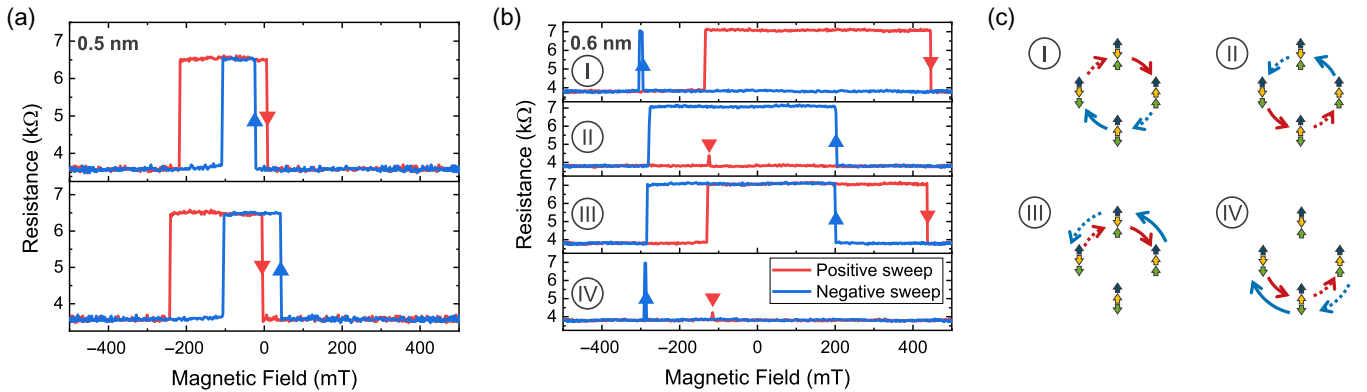


FIG. 7. TMR loops as a function of the external magnetic field, recorded in the same device, for nominal M1 thickness equal to (a) 0.5 nm and (b) 0.6 nm. In the thinner case (0.5 nm), loop-to-loop variations arise from the instability of the M1 Co layer, whereas in the thicker case (0.6 nm) they are attributed to PMA competition between M1 and M2 SAF sublayers. (c) Schematic illustrations summarize the different switching sequences observed in the same device, highlighting the role of thermal fluctuations in determining the sequence.

shown in Figs. 7(b) and 7(c), and can be summarized as follows.

(i) *M1-dominated SAF*. This TMR loop aligns sharply with the one displayed in Fig. 2(c) in the main text, reflecting M1 dominance.

(ii) *M2-dominated SAF*. The TMR loops align with the central graph of Fig. 2(b), resulting in M2 dominance. Notably, the RL and M1 switching fields overlap, preventing the TMR signal from reaching the antiparallel resistance state.

(iii) *Mixed case (M1-dominated in positive sweep, M2-dominated in negative sweep)*. During the positive field sweep, M1 switches after zero field, reflecting M1 dominance. During the negative sweep, M1 switches before zero, showing M2-dominated behavior. The resulting TMR loop aligns with the positive minor loop in the central graph of Fig. 2(b) (green curve).

(iv) *Mixed case (M2-dominated in positive sweep, M1-dominated in negative sweep)*. Similar to the previous case, but with reversed dominance in the two sweeping directions. Here, the resulting loop corresponds to a negative minor TMR loop. Also in this case, the RL and M1 switching fields are close to each other, preventing the TMR signal from reaching the antiparallel resistance state.

APPENDIX E: EXTERNAL AND EXCHANGE COUPLING FIELD COMPETITION IN STT SWITCHING AT SAF ACTIVATION FIELD

The field-assisted STT enables the determination of the SAF activation field by identifying the threshold field at

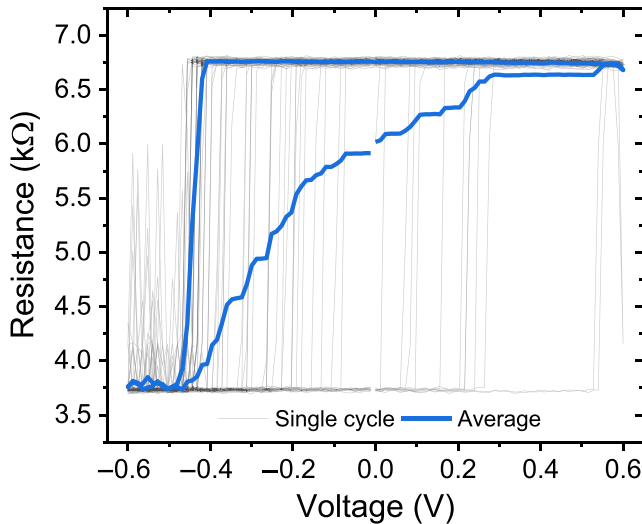


FIG. 8. One Hundred STT loops (average shown in blue) collected at an applied external field of 230 mT, corresponding to the SAF activation field. The results show competition between exchange and external magnetic fields in reversing the M1 Co layer. Thermal variations determine the switching behavior of each individual STT loop.

which the switching voltage significantly drops. However, this transition is not abrupt, evidenced by significant variability in STT loops near the SAF activation field, as described below.

Figure 8 shows 100 repetitions of STT loops at a field equal to the SAF activation field. A notable loop-to-loop variation is observed, reflecting the stochastic nature of the switching process. In this scenario, the STT drives the $AP \rightarrow P$ transition, corresponding to the reversal of the M1 layer and the parallel alignment of the two SAF sublayers. This switching is simultaneously supported by the external magnetic field and opposed by the exchange coupling field, creating a dynamic competition between the two fields. Here, thermal variations are crucial in determining whether the external magnetic field or the exchange coupling dominates, leading to the observed loop-to-loop variability.

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