Time-Resolved Detection of Multilevel Switching of the Magnetization and Exchange Bias Driven by Spin-Orbit Torques

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Article

Keywords: current induced magnetization switching, spintronic devices, Pt/Co/IrMn heterostructures

Posted Date: September 14th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-882472/v1>

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Version of Record: A version of this preprint was published at Nature Electronics on November 28th, 2022. See the published version at <https://doi.org/10.1038/s41928-022-00870-3>.

Abstract

Current induced magnetization switching, jointly with the manipulation of exchange bias, via spin-orbit torques (SOT) on sub-nanosecond timescales hold great promise for fast and low-power spintronic devices. Specifically, the time-resolved detection and subsequent analysis of switching trajectories relevant to ferromagnet/antiferromagnet exchange biased structures are central to designing SOT devices with high speed, and are still open questions. Here, we report the SOT-induced multileveled switching on sub-nanosecond timescales in Pt/Co/IrMn heterostructures, and illustrate the time-resolved magnetization switching trajectories of the exchange bias. By adopting time-resolved magneto-optical Kerr microscopy combined with micromagnetic simulations, our work reveals that not only the ferromagnets, but also the multiple antiferromagnetic domains and exchange bias, can be partially switched by sub-nanosecond current pulse, to flexibly control the switching probabilities at multiple levels. The experiments demonstrate that the SOT switching of exchange bias, which immediately depends on the current density, can significantly stabilize the multileveled magnetization switching within sub-nanosecond current pulse with high thermal stability.

Main Text

Spintronic devices based on spin-orbit torques (SOT) have emerged as crucial candidates for future nonvolatile memory devices with low power consumption and high operation speed¹⁻³. Developed from the initial SOT devices comprising heavy metal/ferromagnet (FM)/Oxide trilayers^{4,5}, the introduction of FM/antiferromagnet (AFM) structures with in-plane exchange bias has extra benefits. In addition to the advantage of inducing an internal effective field through the exchange bias effect to enable field-free SOT switching⁶⁻⁸, a second benefit is that optimized structures also provide a flexible approach to manipulate the AFM spins through energy-efficient SOT switching^{9,10}. The reversal of FM accompanied by the switching of exchange bias also has technological importance for realizing robust magnetization switching with high thermal stability. In view of the intrinsic high frequency response of AFMs^{11,12}, gaining insight into the magnetization dynamics as well as into the time-resolved switching process of SOT devices comprising FM/AFM is of great interest, since this lays the scientific foundation for designing SOT devices with ultrafast switching speed.

Recent studies have shown that the perpendicular exchange bias at FM/AFM interfaces can be switched by SOTs, which are either generated from the heavy metal Pt in Pt/Co/IrMn⁹, or from the AFM IrMn in IrMn/CoFeB¹⁰. The independent manipulation of the perpendicular magnetization and the interfacial exchange bias in the FM/AFM system could improve the plasticity and stability of potential devices towards practical applications. However, these recent experiments have focused on examining the final magnetic state long after a current pulse has passed, while investigations of the details of magnetization dynamics and in particular the time scale of switching of the exchange bias are still missing. On a different note, multiple switching levels have also been reported as a unique character for FM/AFM

systems^{6,13}, and are generally related to fragmented domain structures in the AFM¹⁴. To clarify the underlying switching mechanisms, experiments addressing magnetization dynamics on time scales of the precession frequency and time-resolved measurements of the trajectories of the AFM based multileveled SOT switching processes are fundamentally important. Time-resolved magneto-optical Kerr effect (TR-MOKE)^{15,16} and X-ray transmission microscopy¹⁷ studies could provide direct approaches on detecting the magnetization reversal process on picosecond time scales. In parallel, several theoretical models including the macrospin approximation and micromagnetic simulations have been adopted to elucidate the SOT induced dynamics^{15,17,18}. In spite of the great efforts on exploring the magnetization dynamics during the SOT switching process, the dominating roles either coherent switching or domain nucleation and propagation are still largely open questions for the FM system, let alone for FM/AFM structures with exchange bias. Finally, the high operating frequencies and particular multidomain structures of AFMs could offer more flexible switching states and steerable switching processes, which deserves in-depth study.

In this article, we report SOT-induced multileveled switching of the *magnetization* as well as the *exchange bias* on sub-nanosecond timescales in Pt/Co/IrMn heterostructures. By adopting time-resolved MOKE microscopy combined with micromagnetic simulations, we demonstrate that the magnetization as well as the exchange bias can be switched within the applied current pulses of nanosecond duration. In particular, our work reveals efficient and ultrafast manipulation of the multiple AFM domains through current induced SOTs, leading to multiple and reproducible switching levels that can be flexibly modulated by external magnetic fields, current density and current pulse length. This essential study of spin dynamics during the SOT switching process could add new perspectives on designing ultrafast and energy-efficient spintronic devices based on AFMs, and might prove useful for potential applications in neuromorphic computing devices^{13,19}.

Device, set-up and time-resolved SOT switching

Stacks of Ti(5)/Pt(5)/Co(1.2)/IrMn(8)/Ti(2) (in nm) were deposited on Si wafers by magnetron sputtering at room temperature. To induce both, out-of-plane and in-plane exchange bias in this system, the samples were annealed at 200 °C under a tilted in-plane magnetic field of 9 T, such that exchange bias fields of 35 mT and 55 mT were observed in the out-of-plane and in-plane hysteresis loops, respectively [Supplementary Note 1]. Then the film was structured into $2 \times 2 \mu\text{m}^2$ squares, which were integrated into 50 Ω matched Au microstrips to ensure good transmission of short current pulses (Fig. 1a).

Out-of-plane hysteresis loops of the $2 \times 2 \mu\text{m}^2$ device are recorded by local static MOKE measurements, where the laser is focused on the center of the square. As shown in Fig. 1b, a shift of the loop towards the

negative direction is observed, with an out-of-plane bias field of 35 mT. To investigate the magnetization dynamics during the SOT switching, a pump-probe TR-MOKE experiment is carried out. A simplified block diagram of the experimental setup is depicted in Fig. 1c. In these experiments, the magnetic systems are pumped by a pulse train of alternating positive and negative current pulses generated using an arbitrary waveform generator (AWG), which is triggered by the laser pulses. The AWG output pulse train is amplified by a broadband amplifier to a maximum voltage amplitude of ± 5 V and fed into a 50 Ω matched high frequency line. To study the switching process in detail, a lock-in technique is used to enhance the signal to noise ratio. Switching experiments of perpendicularly magnetized elements using SOT are usually performed in an externally applied in-plane magnetic field necessary to break the symmetry, which is applied along the x -direction in our experiments. Note, however, that in the present experiments the in-plane exchange bias can provide symmetry breaking as we will further explain below.

A typical measurement result over one full period of 200 ns is illustrated in Fig. 1d. The positive and negative current pulses in the sequence are 1 ns long, and have a separation of 100 ns in the whole 200 ns range. Current pulses with a peak current density of $|j_{\max}| = 1.7 \times 10^{12}$ A/m² are adopted to switch the magnetization in an in-plane static magnetic field of $B_x = 100$ mT. The lower panel of Fig. 1d displays the Kerr signal of the device, which is normalized by the saturated Kerr rotation. The time traces show that the magnetization of Co switches from the “up state” (+ z direction) to the “down state” ($-z$ direction) during the first positive pulse and from down to up during the second negative pulse. Concerning the direction of the observed switching, the SOT from Pt dominates in the device although spin currents from both Pt and IrMn exert torques on Co. This is consistent with the fact that the current density flowing through IrMn (1.6×10^{11} A/m²) is one order of magnitude smaller than that of Pt (1.7×10^{12} A/m²), while the spin Hall angles of IrMn and Pt are similar in magnitude^{20,21}. Note that the switching between opposite saturated states occurs almost within the duration of current pulses, which demonstrates that there is no significant delay or after-pulse relaxation.

Time-resolved multilevel magnetization switching

To understand the switching trajectory of the magnetization in more depth, we focus on the reversal process as a function of time during the first 3 ns. The switching processes for different applied in-plane magnetic fields B_x are summarized in Fig. 2a. It is clear that magnetization switching starts with the emergence of the current pulse and finishes shortly after the 1 ns pulse. Interestingly, different stable levels of Kerr intensity are reached with various B_x . First, one should note that the recorded Kerr signal here reflects the probability of the switching events over several thousand times due to the statistical averaging of the pump-probe technique. When B_x reaches 100 mT, full switching of the magnetization towards the z -direction is achieved, while applying larger B_x tilts the magnetization into the plane towards the direction of B_x resulting in a decreased Kerr intensity¹⁵ [Supplementary Note 2]. When B_x is smaller

than the critical field of 100 mT, the Kerr intensities (switching probabilities) decrease significantly with decreasing magnetic field. Note that the Kerr intensities for different B_x are quite reproducible for multiple measurements of different devices, indicating the good stability and endurance of SOT induced magnetization switching in such structures. Although this multileveled phenomenon has been reported in static switching of AFM-ferromagnet bilayer systems^{6,13}, the magnetization dynamics of the multileveled time-resolved switching trajectory on the time scale of nanoseconds remains to be clarified, which is in the focus of this work.

When the external magnetic field is removed, reversal of the magnetization solely by positive/negative current pulses can still be recognized, as shown in Fig. 2b. It has been well understood that the internal in-plane exchange bias can provide an effective field to break the symmetry^{6–8}, acting similarly as the external magnetic field B_x . Although a considerable in-plane exchange bias of 55 mT is induced in the film stack by annealing (Supplementary Note 1), it decays to be smaller than 20 mT for the small $2 \times 2 \mu\text{m}^2$ device due to the fabrication process. Accordingly, the relatively low level of the switching probability indicates that only a small part of the magnetic domains is switched. Note that the two peaks at 0 ns and 101 ns are due to noise in the reflectivity stemming from the boundary of the device and originating from Joule heating. Nevertheless, even in the absence of the external magnetic field, the partial switching is still fast and finishes within a short time of 3 ns.

The time-resolved switching process as a function of pulse length and current density is further studied to gain insight into the factors contributing to partial switching. Fig. 2c summarizes the reversal of the magnetization for different pulse lengths, with B_x fixed at 100 mT and a current density of $1.7 \times 10^{12} \text{ A/m}^2$. As the pulse duration decreases from 1 ns to 0.4 ns, the switching probability decreases dramatically because a larger threshold current density is needed for full switching at shorter pulse durations. This indicates that thermal activation must be included to explain SOT switching in such devices^{22–24}. Moreover, magnetization switching mostly finishes within the pulse length and subsequently stops at certain levels, exhibiting distinct partial switching behaviors related to different pulse durations. Above a pulse length of 1 ns, full switching is achieved and further increasing the pulse length to 1.3 ns does not change the switching process anymore. Apart from the pulse length, partial switching also depends on the applied current density as can be seen in Fig. 2d. In particular, at low current densities magnetization switching stops at certain levels, persists during the pulse, and then relaxes immediately after the pulse. This behavior indicates that the switched magnetic domains in Co stop their growth due to a weaker torque induced by a smaller current density^{1,10,15}, and are shrunk after the pulse due to a competition between the SOT and the pinning from the interfacial exchange bias, which will be discussed later. As the current density reaches $1.6 \times 10^{12} \text{ A/m}^2$, full switching of Co magnetization is achieved, leading to a nonvolatile switching behavior. Furthermore, it is clear from Fig.

2c,d that the initial switching speed stays almost the same for different pulse widths and current densities, indicating that the reversal dynamics at the initial stage are independent of current density and pulse length.

Quasi-static magnetization switching based on multi-domains

In order to clarify the physical mechanism of partial switching in low fields, a control experiment of static switching is carried out. This has the great advantage that it enables us to distinguish the switching behavior for each individual pulse, instead of performing statistical averaging as in the time-reversed measurements. Static switching in real time is implemented on the same optical setup but on a larger device of $5 \times 5 \mu\text{m}^2$, and using a relatively long current pulse length of 1 ms with a current density of $9.5 \times 10^{11} \text{ A/m}^2$. The measurement sequence with different B_x is shown in Fig. 3. The magnetization is switched by positive/negative current pulses and a magnetic field B_x of 100 mT is applied only when time (t) is in the range of $0 \text{ s} < t < 50 \text{ s}$, $100 \text{ s} < t < 150 \text{ s}$, and $200 \text{ s} < t < 250 \text{ s}$. When the magnetic field is applied, the magnetization is fully switched between up and down states. In particular, the magnetization is always partially switched around its initial state when the magnetic field is turned off ($50 \text{ s} < t < 100 \text{ s}$ and $150 \text{ s} < t < 200 \text{ s}$).

To understand the result, we should mention that multiple domains tend to form during the switching, especially in the multilayered structures related to AFM, which has been reported in recent work^{13,14}. Compared to the non-exchange-biased devices where the domain walls can easily propagate during the switching, here the Co domains are pinned by the multiple domain structures of IrMn. The nucleation and reversal of Co domains during the pulse is linked to the switching of uncompensated IrMn domains. Accordingly, the recorded Kerr signal (also indicated as the normalized perpendicular magnetization m_z) for each pulse averages the signals of several magnetic domains, as illustrated in the bottom schematics in Fig. 3. For example, at 100 s, the nearly zero level of m_z means that upward spins and downward spins are distributed equally in the spot area. To be noted, no clear domain patterns are observed from the MOKE microscopy during the time-resolved switching, also indicating the stochastic domain nucleation within the spatial resolution of 500 nm for our system. In addition, we have also investigated the field dependence of the quasi-static switching process and we observe that full switching of the magnetization is achieved already at rather low fields of 10 mT [Supplementary Note 3], compared to fields of the order of 100 mT required for the fast switching as shown in Fig. 2a. This is mainly because longer current pulses would result in a higher possibility to overcome the energy barrier for the switching because of thermal activation, and this is also the reason why the multi-step SOT switching has not been observed in previous reports regarding quasi-static experiments^{9,10}. Importantly, in this exchange coupling system the quasi-static MOKE measurements crucially support the multi-domain switching scenario, which is the dominating mechanism for the multilevel SOT switching.

Time-resolved SOT switching of the interfacial AFM spins

Next, we focus on the Co/IrMn interface with strong exchange coupling to illustrate the microscopic fast manipulation of the antiferromagnetic spins. After switching the magnetization in the same device as discussed in Fig. 2 using a negative current pulse of 1 ns duration and with $j_c = 1.7 \times 10^{12}$ A/m², the static polar Kerr signals are recorded by sweeping the out-of-plane fields to investigate the perpendicular exchange bias. The Kerr signals are detected using the same method to the quasi-static observations. As shown in Fig. 4, the measurements are carried out in two different sequences. First, the device is switched with an in-plane field of -100 mT, to ensure that the Co moments are fully set to the downward state after the negative current pulse. Surprisingly, even after a short pulse of 1 ns duration, the out-of-plane loop shown in Fig. 4a has a significant shift towards positive fields, which is opposite to the original loop shown in Fig. 1b. The reversal of the exchange bias indicates that not only the magnetization of Co is switched from up to down, but also the interfacial spins of IrMn are reversed (Fig. 4a), due to the current-induced SOT and the exchange coupling at the Co/IrMn interface. This implies that the switching of the exchange bias occurs even with the short current pulse, which has not been reported, yet. Subsequently, switching is performed using a pulsed current and an in-plane field of $+50$ mT. As a result, the exchange bias is shifted towards the negative direction with a gradual slope. In accordance with the partial switching scenario displayed in Fig. 2a, a part of the Co magnetization is switched upwards, accompanied by partial switching of the interfacial IrMn spins. We observe that the out-of-plane loop is broadened and tilted due to the dispersion of both, magnetization and exchange bias, in multiple domains. Thereafter, the device is reset with an in-plane field of -100 mT, and it is confirmed that the out-of-plane exchange bias changes back to positive, indicating that the interfacial IrMn spins are tilted downwards again (Fig. 4c). At last, the magnetization is switched by a short pulsed current without applying any external magnetic field. According to the rather weak change of the magnetization in zero magnetic field as shown in Fig. 2b, only a small volume of the Co magnetization is switched upwards (Fig. 4d). It is then simply assumed, that the exchange bias would remain positive as in the situation for -100 mT. However, the out-of-plane bias field has almost vanished after switching, indicating that the exchange bias is now distributed randomly, in contrast to the domain structure in the Co film. As illustrated in the lower panel of Fig. 4d, this strongly supports the idea that the SOT pulse can disturb the original equilibrium state of the interfacial AFM spins, even when deterministic switching of FM is negligible. This is meaningful for the efficient manipulation of AFM spins within nanoseconds, since usually field annealing above the Néel temperature of the AFM is necessary for modulating the exchange bias^{11,25}. Note that Joule heating can be excluded as the origin of the exchange bias reversal since the local heating by the short current pulse is not sufficient to anneal the AFM, because the temperature rise is much too low to bring the AFM above the blocking temperature^{9,15}.

The measurements performed for another pulse sequence in Fig. 4e-h again confirm this phenomenon. After switching in an in-plane field of +100 mT, the out-of-plane exchange bias is set to the negative direction (Fig. 4e), which can be reversibly manipulated (Fig. 4a). For the partial switching at –50 mT, some of the interfacial spins in the AFM are tilted from the up to the down state, in correspondence with the situation for +50 mT. In contrast, for the case of zero-field switching after setting the exchange bias by +100 mT, the negligible bias field substantiates the disturbance of the interfacial IrMn spins by SOT. Therefore, the static polar MOKE measurements performed after the fast SOT switching process convincingly demonstrate that in addition to the switching of the ferromagnetic magnetization, the interfacial AFM spins as well as the exchange bias can be reversed by current pulses as short as 1 ns.

Micromagnetic simulations of time-resolved exchange bias switching

To further investigate the fast reversal process of the Co magnetization and the exchange bias, micromagnetic simulations are performed using MuMax3 (Ref.^{26,27}). In the simulations, to set a reasonable exchange bias of the system, the interfacial AFM spins are assumed to be antiferromagnetically coupled to the AFM bulk part and ferromagnetically coupled to Co, as described in the Methods and Supplementary Note 4. To obtain a quantitative understanding of the partial SOT switching in the experiments, the magnetic field dependence and the current density dependence of the magnetization switching process are simulated. The results closest to the measurements are reached for a field-like torque (τ_{FL}) $\tau_{FL}/j_c =$ and damping-like torque (τ_{DL}) $\tau_{DL}/j_c =$ (Ref.^{15,28}). As displayed in Fig. 5a, the switching speed increases with increasing the magnetic field and the behavior matches to the experimental result. Moreover, multileveled switching of the FM magnetization is obtained by varying the external magnetic field. Note that we do not include Joule heating in the micromagnetic simulation. Since similar switching times of about 1.5 ns are observed in the simulations and the measurements (Fig. 2a), we exclude a dominant role of thermal effects for the switching process. This is in agreement with the fact that if a heating effect was prominent, several nanoseconds would be required after the application of the current pulse to recover the initial temperature¹⁵.

Meanwhile, the switching of m_z strongly depends also on the current density, as summarized in Fig. 5b and 5c. This is due to the proportional relationship between current induced torques (including τ_{FL} and τ_{DL}) and injected spin current¹, that larger torques will lead to more complete switching of the multiple domains. For the switching without external fields, larger current density is needed compared to the switching with applied fields (Fig. 5c), which agrees to the experimental result. When we look into the switching processes as a function of time, it is found that the simulated results differ from the experimental cases shown in Fig. 2d, which will be discussed later.

Inspiringly, the reversal of the exchange bias by SOT switching is successfully reproduced in the simulations. To have a visual understanding of the partial switching of the magnetization and the reversal of the exchange bias, the spatially resolved domain evolution during the fast SOT switching process is calculated and displayed in Fig. 5d,e. The imprinted domain patterns as well as the synchronous propagation of domain walls in Co (upper row) and interfacial IrMn (bottom row) indicate strong coupling between the FM and the interfacial AFM spins. This result indicates that the SOT reverses both the FM spins and the interfacial AFM spins, matching to the proposed model for exchange bias reversal discussed in Fig. 4. Distinct from the system without AFM, where either coherent switching of a single FM domain or propagation of a tilted domain wall dominates^{15,17}, multiple domains tend to form in the AFM and seem to have immediate impact on the magnetization switching of the neighboring FM. As shown in Fig. 5d for relatively small j_c , random domains nucleate in the AFM as the current pulse emerges, simultaneously with the nucleation of the FM domains. During the 1 ns pulse, propagation of the domain walls takes place. The multiple domain patterns in the FM finally stabilize at about 6 ns, resulting in the multileveled m_z after switching. While for the j_c larger than the threshold ones (Fig. 5e), much faster process for full switching within 1 ns is observed, in accordance with the time-resolved m_z recorded in Fig. 5b. From the evolution of the images of the domains, it can be concluded that the fast SOT switching is dominated by a combination of homogeneous switching and domain wall propagation in both FM layer and AFM interfacial layer.

Finally, we discuss the time evolution of m_z both in the experiment and simulation (Fig. 2 and 5) to analyze the magnetization dynamics during the fast switching. Note that the switching of exchange bias needs higher threshold current density than that of FM magnetization, which has been recently reported by S. Peng *et al.*¹⁰. In our experiment shown in Fig. 2d, the switching condition of $j_c = 0.9 \times 10^{12} \text{ A/m}^2$ and $B = 100 \text{ mT}$ gives such high torque that the FM switching speed is saturated but not strong enough for exchange bias switching. Hence, the FM stops switching as a result of the competition between the current induced SOT and the unswitched exchange bias during the pulse. Then some of the reversed Co domains relax back after the current pulse, due to the pinning by the unswitched IrMn spins. By increasing the current, larger amount of uncompensated AFM spins are switched and the intermediate level of FM gets higher due to the switching of exchange bias. Consequently, both of FM and exchange bias are fully switched for the current density of $1.7 \times 10^{12} \text{ A/m}^2$. In addition, the field dependence of time-resolved switching in Fig. 2a also confirms the higher threshold for exchange bias switching. Since the slope of the switching loop depends on the magnetic field and no relaxation is observed after the pulse, the switched area of uncompensated AFM spins is as large as the area of FM switching in the condition of $j_c = 1.7 \times 10^{12} \text{ A/m}^2$. Besides, for the situation with a shorter current pulse of 400 ps where the peak of current density is attenuated by $\sim 15\%$ compared to that of 1 ns, the decrease of Kerr intensity after the pulse further supports this crucial idea (red squares in Fig. 2c). Nevertheless, both of the field dependence and the current dependence in the simulation show that the slope varies with the torque strength and m_z does not stay at certain level during and after the pulse. This indicates that the

difference of threshold is negligibly small in the simulation. It is possibly explained by ignored small Joule heating or by the interfacial AFM spins having large thickness despite that sub-lattice spins organize in a magnetic order in real AFM, which is the limitation of micromagnetic simulations.

To sum up, the time-resolved experiments significantly demonstrate that the current density dominates the switching threshold of FM and exchange bias, which responds within sub-nanosecond. Meanwhile, the exerted torques by external in-plane field provide the driving force for SOT switching, that determine the switching probabilities of the multiple domains and influence the switching speed. Based on this switching trajectories within sub-nanosecond timescale, one should mention that the SOT switching of EB in FM/AFM structures has technological significance for the ultrafast operation of SOT-MRAM. On one hand, the multi-domain structures contribute to the multileveled switching of magnetization, which can be easily tuned by different fields, current density and pulse length. This would provide great flexibility for practical applications in multi-bits memory for neuromorphic computing. On the other hand, the reversal of magnetization accompanied by the switching of EB is beneficial for obtaining robust switching of magnetization with high thermal stability. As a comparison of the switching trajectories between field dependence and current density dependence (Fig. 2), it is verified that stable switching levels without relaxation are obtained when the exchange bias is simultaneously switched. The switching in sub-nanosecond also excludes the thermal effect, in contrast to previous reports on Pt/Co/Al₂O₃ without AFM¹⁵. It is then predicted that the SOT switching of exchange-biased domains has great advantages for reducing the device size meanwhile maintaining high stability, which could be robust against field and thermal perturbations in practical applications.

Conclusions

We have reported the time-resolved switching of the magnetization as well as the exchange bias on sub-nanosecond timescales, which are driven by current-induced SOT. Benefiting from the SOT-activated multiple domains at the interface of FM/AFM in Pt/Co/IrMn heterostructures, multileveled switching of the magnetization is achieved within one nanosecond, exhibiting non-volatile and reproducible states. Specifically, time-resolved magneto-optical Kerr microscopy combined with micromagnetic simulations provide valuable insights into the SOT-induced magnetization dynamics with time and spatial evolution. Firstly, multileveled switching of magnetization within one nanosecond is verified to be immediately related to the fast and random nucleation and propagation of multiple domains both in FM and AFM, neglecting unremarkable heating effect. Secondly, invertible switching of exchange bias is primarily achieved on sub-nanosecond timescales, which could significantly stabilize the reversed FM moments within the current pulse, owing to the interfacial exchange coupling. This essential study of multileveled SOT switching, which can be flexibly modulated by external magnetic fields, current density and current pulse length, would provide great superiority towards designing ultrafast and multi-bits memory for neuromorphic computing.

Methods

Samples. Magnetic stacks of Ti(5)/Pt(5)/Co(1.2)/IrMn(8)/Ti(2) (in nm) were grown by magnetron sputtering, which were directly deposited onto high-resistivity Si wafers to ensure a good thermal conductivity. Then the films were annealed at 200 °C in vacuum under an almost in-plane magnetic field of 9 T. The small tilt towards the out-of-plane direction of the annealing fields guaranteed both of out-of-plane and in-plane exchange bias in the sample. The films were further fabricated into squares ranging from $2 \times 2 \mu\text{m}^2$ to $5 \times 5 \mu\text{m}^2$, which were integrated into a 50 Ω matched Au microstrip. Note that the in-plane exchange bias of $2 \times 2 \mu\text{m}^2$ device descends to less than 20 mT due to the heating effect of the fabrication process, in contrast to a well-sustained in-plane exchange bias of 55 mT in $5 \times 5 \mu\text{m}^2$ device similarly to the annealed full films.

Experimental set-up for time-resolved magnetization switching. For the time-resolved pump-probe experiment, a current pulse train of alternating positive and negative pulses serves as the pumping source, which is generated using an arbitrary waveform generator (AWG) connected to a broadband amplifier, and triggered by the laser pulses. The positive and negative current pulses in the sequence are 1 ns long, and have a separation of 100 ns in the whole 200 ns range, corresponding to an output frequency of 5 MHz. The laser pulse train of a 80 MHz Ti:Sapphire laser is reduced to 5 MHz using a pulse picker unit to match the repetition rate of the current pulses. The Kerr signal is recorded using a 100 ps timestep and read out from the photo detector. To enhance the signal to noise ratio and reduce the measurement time, a Lock-in technique with modulation is used.

Quasistatic MOKE measurements

The quasistatic MOKE measurements in real time are implemented on the same optical setup. In order to reveal the real signal, the out-of-plane loop after time-resolved SOT switching is recorded by averaging 10 measurements without any modulation. As shown in Fig. 4, the measurements are carried out in two different sequences. Note that the device is switched by 1 ns-long positive and negative pulses at a frequency of 37 kHz and we stop switching after the negative current pulse, followed by the static polar Kerr measurements.

Micromagnetic simulations. Micromagnetic simulations were performed by using MuMax3, to investigate the ultrafast partial switching of the magnetization²⁵. In the simulations, the cell size is set to $3 \times 3 \times 1.2 \text{ nm}^3$ and the entire geometry is $1.536 \mu\text{m} \times 1.536 \mu\text{m} \times 3.6 \text{ nm}$. The material parameters of Co are chosen as: the saturation magnetization is $5.5 \times 10^5 \text{ A/m}$, the damping constant is 0.5, and the stiffness constant of each layer is $1 \times 10^{-11} \text{ J/m}$. To mimic the exchange coupling in both directions (in-plane and out-of-plane), we have different interfacial coupling at the two interfaces. The top antiferromagnetic layer (AFM2) and the interfacial AFM layer (AFM1) are antiferromagnetically coupled with a stiffness constant of $-1 \times 10^{-11} \text{ J/m}$, and the AFM1 and the ferromagnetic layer (FM) are weakly coupled with a stiffness constant of $3 \times 10^{-14} \text{ J/m}$. By introducing a unidirectional anisotropy along the out-of-plane direction to FM and AFM1, both the out-of-plane exchange bias and the easy axis of the ferromagnetic layer are set.

Here, the anisotropy constants of FM and AFM1 are set as 3×10^5 J/m and 6×10^6 J/m, respectively. A pulse current is applied along the z-direction and only to the FM layer. The magnetization dynamics is calculated for a duration of 30 ns, which is much longer than the current pulse length (1ns).

Data availability

The data that support the findings of this study are available from the corresponding author on request.

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Declarations

Acknowledgements

Y. Wang is grateful for the support from the Alexander von Humboldt Foundation. This work is financially supported by the National Natural Science Foundation of China (Grant No. 62174095), German Science Foundation (DFG) via SFB 1277, and the Natural Science Foundation of Beijing Municipality (Grant No. JQ20010).

Author contributions

C.H.B. and Y.W. planned the study. Y.W. fabricated the devices, collected and analyzed the data. T.T. and D.Z. carried out the micromagnetic calculations. P.L. and C.L. grew the samples and performed the magnetization measurements. Y.W., A.N., and J.S. carried out the magneto-optical Kerr effect measurements. Y.W. wrote the manuscript with input from T.T., C.H.B., S.C., H.W. and Q.D.. All authors discussed the results.

Competing interests

The authors declare no competing interests.

Figures

Figure 1

(a) Schematic of the sample structure and measurement configuration. The size of the structured multilayers is $2 \times 2 \mu\text{m}^2$ (b) Static polar Kerr measurement recorded in the center of the element. (c) A simplified block diagram of the experimental setup. (d) Time resolved measurement of magnetization reversal (bottom) for in-plane $B_x = 100 \text{ mT}$, with a current pulse train (top) as transmitted through the multilayers. For the whole 200 ns range, one positive current pulse and one negative current pulse with pulse lengths of 1 ns each are shown.

Figure 2

Reversal of the magnetization as a function of delay time. (a) Time-resolved magnetization switching for a negative SOT pulse and for different in-plane B_x . (b) Magnetization reversal in zero magnetic field B_x for the positive and negative current pulses as a function of delay time. (c) Measurements for $B_x = 100 \text{ mT}$ and current pulse length τ_P ranging from 0.4 ns to 1.3 ns. The data in (a) and (c) are recorded for the negative pulse and with a fixed current density of $1.7 \times 10^{12} \text{ A/m}^2$. For $\tau_P \leq 1 \text{ ns}$, the reset pulse (positive current pulse) is 1 ns long. For $\tau_P > 1 \text{ ns}$, the negative and positive current pulses have the same length. (d) Measurements for $\tau_P = 1 \text{ ns}$, $B_x = 100 \text{ mT}$ and current densities ranging from 0.9 to $1.7 \times 10^{12} \text{ A/m}^2$.

Figure 3

Quasistatic current induced magnetization reversal with a sequence of different external B_x . The current pulses are 1 ms long. The lower panel shows the schematic of the multiple domains in Co with different arrangements of magnetic moments.

Figure 4

Static polar Kerr measurements recorded after time-resolved switching with a negative current pulse (1 ns long, $j_c = 1.7 \times 10^{12} \text{ A/m}^2$) with different B_x . The lower panel of each figure shows the schematic of the multidomain structures and spin orientations in Co and IrMn.

Figure 5

Micromagnetic simulations of the time-resolved SOT switching process. (a) Magnetization switching for different magnetic fields. The applied current pulse with the peak value of 2.6×10^{12} A/m² is also plotted as the grey trace. (b) Time-resolved magnetization switching for different current density, where external field is absent. (c) Current density dependence of switching probabilities at 0 mT and 100 mT, respectively. (d,e) Snapshots recorded at distinct times of the domain evolution in Co (upper row) and the interfacial IrMn spins (bottom row) for a switching process without external magnetic field, where j_c are set to (d) 2.8×10^{12} A/m² and (e) 3.8×10^{12} A/m², respectively.

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