

All electrical sub-nanosecond field-free switching of perpendicular magnetization with high magnetic field immunity

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Spin-orbit torque magnetic random-access memory is a promising next-generation non-volatile memory technology featuring low power consumption, rapid operation, and high endurance. Conventional spin-orbit torque-induced deterministic perpendicular magnetization switching, however, typically requires the assistance of an external magnetic field. While multiple field-free switching strategies have been demonstrated, most suffer from significant limitations. Here, we present a straightforward and reliable approach for field-free switching of perpendicular magnetization utilizing two orthogonal electrical currents. The method employs only conventional heavy metals as spin current sources and enables seamless integration into existing manufacturing lines as it is fully compatible with standard fabrication processes for commercialized spin-transfer torque magnetic random-access memory. Notably, the approach also achieves ultrafast magnetization switching with robust immunity against external magnetic fields along all directions.

As traditional charge-based memories, such as static random-access memory (SRAM), continue to scale down in size, challenges including increased current leakage, limited density scaling, and inherent volatility have become increasingly significant¹. Spin-transfer torque magnetic random-access memory (STT-MRAM)^{2–4}, which stores information in its magnetization state, has emerged as a promising memory technology^{5,6}. Given the fact that STT-MRAM is non-volatile, offers good scalability, and can be easily integrated into a standard complementary-metal-oxide-semiconductor (CMOS) back-end-of-line process flow, it enables a wide range of applications^{3–5,7–10}. Although leading advanced semiconductor foundries have introduced their STT-MRAM products^{11–13}, the shared read and write current paths through the tunneling barrier impose substantial limitations¹⁴. In addition, the

spin polarization of the polarized current in STT-MRAM is collinear with the magnetization of the free layer. As a result, the damping-like spin torque $\tau_{DL} \propto \hat{m} \times (\hat{m} \times \hat{\sigma})$ is zero in the static state, where $\hat{m}$ and $\hat{\sigma}$ represent the direction of magnetization and spin polarization, respectively. Thus, thermal fluctuations and the associated incubation time are required for magnetization switching^{15,16}. To achieve nanosecond (ns) and sub-ns switching time, a large current density is required to be injected through the tunneling junction, which significantly reduces the endurance of STT-MRAM^{9,17}.

Spin-orbit torque (SOT)-MRAM^{18–20}, which utilizes separate read and write paths, effectively reduces the risk of tunneling barrier breakdown^{21–25}. In this context, the spin Hall effect (SHE)^{22,23} in heavy metals, such as Pt, Ta, or W, which converts an in-plane flowing charge

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current J_C (e.g., along the x -direction) into a perpendicularly propagating (along the z -direction) spin current J_S , is the driving force to switch the magnetization direction in SOT-MRAM. In it, the spin polarization of the spin current is orthogonal to the magnetization of the free layer; the SOT reaches its maximum in the initial state, enabling ultrafast switching. Thus, SOT-MARM has emerged as a compelling candidate to mitigate the obstacles associated with speedy operation and high endurance in STT-MRAM. Nonetheless, achieving reliable field-free switching of perpendicular magnetization remains a significant challenge. Specifically, owing to the orthogonal relationship among the spin current, charge current propagation directions, and the spin polarization direction, the perpendicularly propagating spin current induced by the x -direction charge current (J_x) is polarized along the y -direction. Consequently, the damping-like SOT is always oriented along the $-y$ -direction since it follows $\hat{m} \times (\hat{m} \times \hat{y})$, indicating that it can only deterministically switch the in-plane magnetization^{21,23,26}. Therefore, an external magnetic field parallel to the charge current is typically required to break the in-plane mirror symmetry and achieve deterministic switching of the perpendicular magnetization^{21,23}. Incorporating the external magnetic field, however, imposes significant challenges for device integration and application.

Various approaches for field-free SOT switching of perpendicular magnetization have been demonstrated, including introducing inter-layer exchange coupling^{27,28}, in-plane stray fields^{29–32}, in-plane structural²⁶, or compositional^{33,34} asymmetry, tilted anisotropy^{35,36}, low-symmetry single crystalline/magnetic spin current generator^{37,38}, bending current³⁹, out-of-plane spin-orbit torques^{40,41}, competing spin current⁴², gradient spin current^{43,44}, and combinations of STT and SOT⁴⁵, etc. Nevertheless, the majority of these strategies either undermine the stability of the free layer, or reduce the reliability of the tunneling barrier, or are incompatible with wafer-level CMOS back-end-of-line processing. Recently, Suess et al.⁴⁶ conducted a micro-magnetic investigation on the field-free switching of perpendicular magnetization using two orthogonal charge currents. This strategy is based on the conventional spin Hall effect in polycrystalline heavy metals and is, therefore, in principle, compatible with standard fabrication processes for commercial STT-MRAM. The experimental implementation, however, has not yet been demonstrated. In addition, the deterministic SOT-driven perpendicular switching with immunity against external magnetic fields applied along all directions has not been validated in previous studies. This issue, however, is a crucial prerequisite for reliable applications^{47,48}.

Here, we experimentally demonstrate sub-ns field-free switching of perpendicular magnetization driven by two orthogonal electric currents. These currents can be a combination of DC and pulsed currents, or two pulsed currents with a controlled delay. Notably, the switching polarity remains unaffected by external magnetic fields exceeding 30 mT along all directions, thereby meeting the requirements for commercial applications^{47,48}. We further demonstrate purely electronic and controllable information writing and reading in a 5×5 memory array. Our work explicitly demonstrates reliable field-free switching of the perpendicular magnetization in conventional spin Hall materials. In particular, we addressed four critical requirements for SOT-MRAM: (1) field-free switching, (2) ultrafast speed, (3) magnetic field immunity exceeding 30 mT, and (4) CMOS-compatibility. We anticipate that it will facilitate the practical implementation of SOT-MRAM technology in various commercial applications.

Results

Symmetry analysis of SOT-induced switching of the perpendicular magnetization

In the SOT-induced switching of the perpendicular magnetization (along the z -direction) with a charge current pulse J_x , a mirror symmetry about the xz -plane is preserved. Because the magnetization is a pseudovector, its sign reverses under a mirror operation. Given the

fact that the magnetizations along the $\pm z$ -direction have the same energy, a charge current along the x -direction cannot determine the final orientation of the perpendicular magnetization. From the microscopic viewpoint, J_x will drive the magnetization towards the $-y$ -direction due to the damping-like SOT that follows $\hat{m} \times (\hat{m} \times \hat{y})$. Subsequently, after J_x is removed, the magnetization will randomly switch back to the up/down direction owing to its perpendicular magnetic anisotropy. Thus, additional symmetry-breaking element is required to achieve deterministic switching. This can be achieved by applying a magnetic field parallel to the current. In this scenario, the mirror reflection across the xz -plane reverses both the magnetization and the magnetic field, since both are pseudovectors. Conversely, deterministic switching is possible if the magnetic field direction is fixed, resulting in magnetic field-assisted switching (Fig. 1a). This is due to the out-of-plane torque $\hat{m} \times \hat{H}$ that determines the switching direction upon releasing J_x . Interestingly, a second charge current along the y -direction (J_y) induced a damping-like SOT, which follows $\hat{m} \times (\hat{m} \times \hat{x})$, can also serve as a knob (Fig. 1b). After J_x is turned off, the magnetization will switch back to its easy axis (perpendicular direction) if J_y is below the critical current density. Meanwhile, the initial magnetization component along the y -direction (m_y) determines the final state, where $\hat{m} \times \hat{x}$ denotes the direction of the effective magnetic field. As the effective magnetic field that determines the final state of the magnetization is proportional to the magnitude of J_y , high magnetic immunity of SOT switching is expected with appropriate current pulses. Although we only considered the damping-like torque here, including the field-like torque reduces the critical current density with no change to the overall physics (Supplementary Note 1). A more detailed vector analysis of the equilibrium state for the field-assisted and field-free switching are provided in Supplementary Note 2.

Experimental results

The SOT switching experiments are performed on Ta(1)/Pt(6)/Co(1.2) multilayers deposited on high-resistivity silicon substrates using magnetron sputtering. The numbers in parentheses are the corresponding thicknesses in nanometers. The 1-nm Ta layer serves as the buffer layer, and 6-nm Pt acts as the spin-current track. To protect the sample, a 3-nm Ta film is deposited on the top and naturally oxidized in air. The films are further patterned into standard crossbars with a circular ferromagnet (Co) disk using e-beam lithography and etching. The ferromagnetic disk is ~400 nm in diameter and etched to the Pt layer, with a bar width of ~800 nm. The crossbar is further connected to electrodes to conduct SOT switching and magnetization probing through the measurement of the anomalous Hall resistance, R_{AHE} . We note that all measurements in this work are performed at room temperature. Figure 1c presents a scanning electron microscope (SEM) image of the fabricated device, with the heterostructure stack sketched in the inset of Fig. 1d. Figure 1d shows the R_{AHE} of the device measured using a small DC current $I_{DC} = 100 \mu A$, with the magnetic field sweeping along the out-of-plane direction. The square hysteresis loop indicates that the top Co layer exhibits robust perpendicular anisotropy with a coercivity of ~40 mT.

We first investigate the conventional field-assisted SOT switching using a single charge current pulse (Fig. 2a). R_{AHE} is measured after applying the charge current pulses along the x -direction with different amplitudes to monitor the magnetization direction of the Co layer. The pulse duration of the charge current is set as 10 μs . Consistent with the symmetry analysis presented in Fig. 1a, no deterministic magnetization switching is observed with zero external magnetic field (purple symbols in Fig. 2b). The symmetry can be effectively broken by applying a magnetic field along the electric current direction. The final state of magnetization is thus governed jointly by the directions of the current and the external magnetic field. The almost 100% switching is due to the reduced pinning effect in the disk geometry, which has also been observed in several previous reports^{32,49,50}. In addition, we verified that

the possible spin current from the Ta capping layer plays only a minor contribution, as confirmed in a device with a SiO₂ capping layer (Supplementary Note 3).

We further investigate the field-free SOT switching driven by two orthogonal charge currents, as schematically shown in Fig. 2c. Here, a charge current pulse J_x^{pulse} with a 10- μ s duration is applied along the x -direction while a DC charge current $J_y^{\text{DC}} = 30 \times 10^{10} \text{ A} \cdot \text{m}^{-2}$ is applied along the y -direction. The J_y acts as an effective field, which breaks the mirror symmetry and results in deterministic switching after the first SOT pulse is released. Therefore, we achieve field-free electrical control of perpendicular magnetization in this setting. Importantly, reversing the direction of J_y also reverses the polarity of the magnetization switching. This is due to the change of the effective magnetic field direction from the J_y -induced SOT acting on the magnetization. Similar to the field-assisted SOT switching, the switching degree in Fig. 2d is also almost 100% in the field-free SOT switching. When the magnitude of J_y is reduced, the switching probability decreases, resembling the effect of reducing the external magnetic field in field-assisted switching (Supplementary Note 4). The possible influence of the Oersted field along the x -direction generated by J_y can be safely excluded based on the following reasons. Firstly, we estimate that both the maximum x -direction and z -direction Oersted fields experienced by the Co disk are below 1 mT, which have no influence on the perpendicular magnetization switching (Supplementary Note 5). Secondly, the direction of the Oersted field generated by $\pm J_y$ acting on the Co layer is along the $\pm x$ -direction. The expected switching polarity by the Oersted field is thus opposite to our experimental observations (comparing Fig. 2b, d). Therefore, we attribute the field-free switching result shown in Fig. 2d to the spin-orbit torque induced by both J_x and J_y rather than the one assisted by the J_y -generated Oersted field.

To explore the switching speed, both the field-assisted and field-free SOT-driven magnetization switching are further studied by systematically reducing the duration of the pulse J_x^{pulse} . In the latter case, we initially fix the DC charge current as $J_y^{\text{DC}} = 30 \times 10^{10} \text{ A} \cdot \text{m}^{-2}$. The switching loops corresponding to different pulse durations in these two

configurations are depicted in Figs. 3a, c, respectively. As expected, the critical current density J_C required for switching increases as the pulse duration t_p decreases. J_C as a function of t_p are further summarized in Figs. 3b, d, respectively. We find that in both cases J_C can be described by $1/t_p$ (red curves) when $t_p < 10 \text{ ns}$, indicating that the switching speed depends on the efficiency of the angular momentum propagation of the current to the magnetic layer. For $t_p > 10 \text{ ns}$, J_C can be described by $-\lg^{0.5}(t_p)$ (blue curves), suggesting that the thermal fluctuations provide the assistance for the magnetization to overcome the switching barrier. As 5 ns is near the crossover point, both effects coexist. Therefore, this region cannot be accurately fitted using a single function, which may introduce relatively large fitting errors. These findings are consistent with results reported by Díaz et al.⁵¹. Remarkably, deterministic pure electronic switching of perpendicular magnetization with a pulse duration as short as 0.8 ns is realized. The corresponding write energy for this 800-nm width crossbar is estimated to be approximately 60 pJ based on Ohm's law; lower energy consumption is expected when the device size is reduced (Supplementary Note 6). We note that 0.8 ns does not represent the upper limit of switching speed; instead, it is due to the output voltage limit (5 V) of our pulse generator. Faster switching and lower write energy consumption can also be expected by optimizing the Pt layer thickness and reducing the dimensions of the crossbar structure. In fact, micromagnetic simulations predicted that the switching time of 0.1 ns is achievable⁴⁶.

In the SOT-switching with dual currents, the spin current from a DC bias charge current J_y^{DC} serves as the source of an effective field to break the symmetry. The continuous current nevertheless increases the power consumption with excessive Joule heating. By reducing the pulse duration, we can further increase the amplitude of J_y to systematically evaluate the robustness of the switching against the external magnetic field. We thus conduct the SOT-switching with dual current pulses, where the pulse duration of J_x^{pulse} and J_y^{pulse} is set as 0.8 and 2-ns pulses, respectively. With the simultaneously applied current pulses, ultrafast deterministic switching at zero field is also achieved (Fig. 4a). Moreover, the switching polarity reverses when reversing the

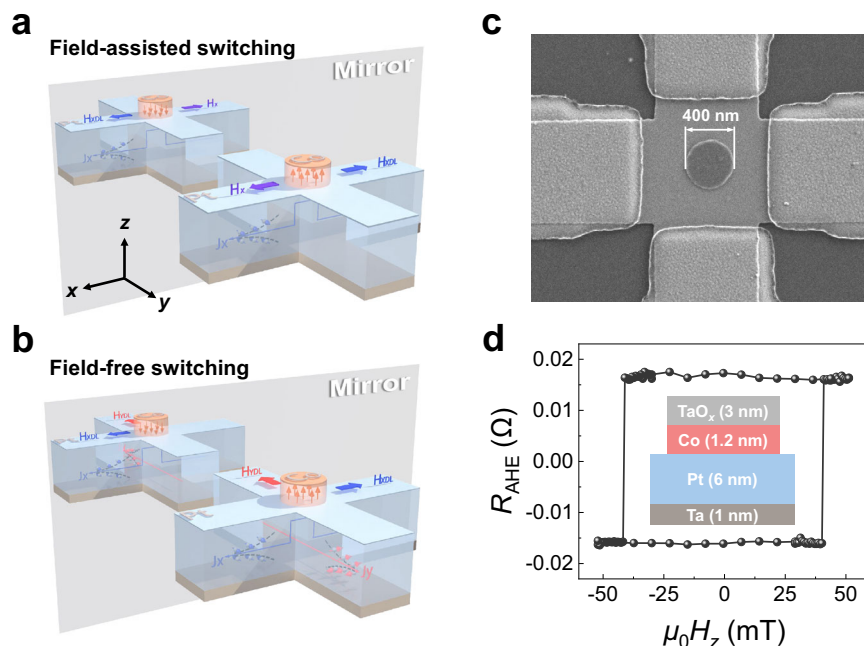


Fig. 1 | Symmetry analysis and device characterization. **a** Field-assisted magnetization switching with symmetry broken by applying an external magnetic field along the electric current direction. **b** Field-free magnetization switching with symmetry broken by a second charge current along the y -direction, J_y . **c** An SEM image of a typical device fabricated via e-beam lithography and etching technique,

showing a crossbar with a bar width of about 800 nm and a disk diameter of about 400 nm. **d** The measured R_{AHE} of the device with the magnetic field sweeping along the out-of-plane direction. The illustration shows the heterostructure with the disk being etched to the Pt layer.

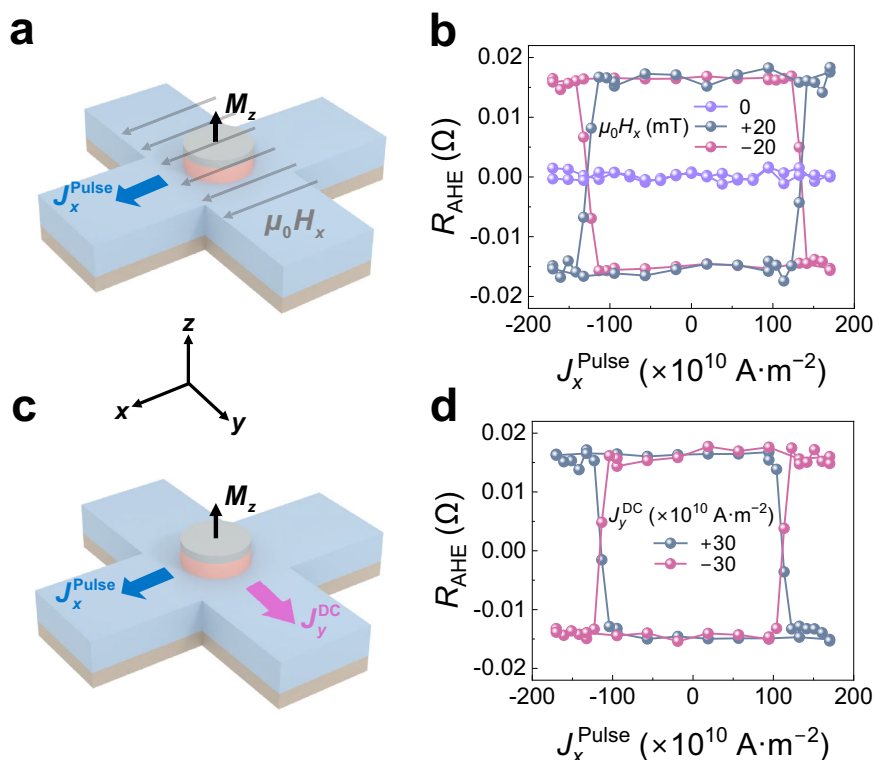


Fig. 2 | Measurement configurations and the results of field-assisted and field-free switching. **a** Schematic diagram of the field-assisted SOT switching device. In this setup, both the pulse current J_x^{pulse} (indicated by a blue arrow) and the external magnetic field $\mu_0 H_x$ (indicated by gray arrows) are applied along the x-axis direction. **b** Field-assisted SOT switching under external magnetic fields with different amplitudes and directions. **c** Schematic diagram of the field-free SOT switching

device. The pulse current J_x^{pulse} (indicated by a blue arrow) is applied along the x-direction, while the DC current J_y^{dc} (indicated by a purple arrow) is applied along the y-direction. **d** Field-free SOT switching with the current density J_y^{dc} applied in the opposite directions. The amplitude of current density J_y^{dc} is fixed as $30 \times 10^{10} \text{ A} \cdot \text{m}^{-2}$.

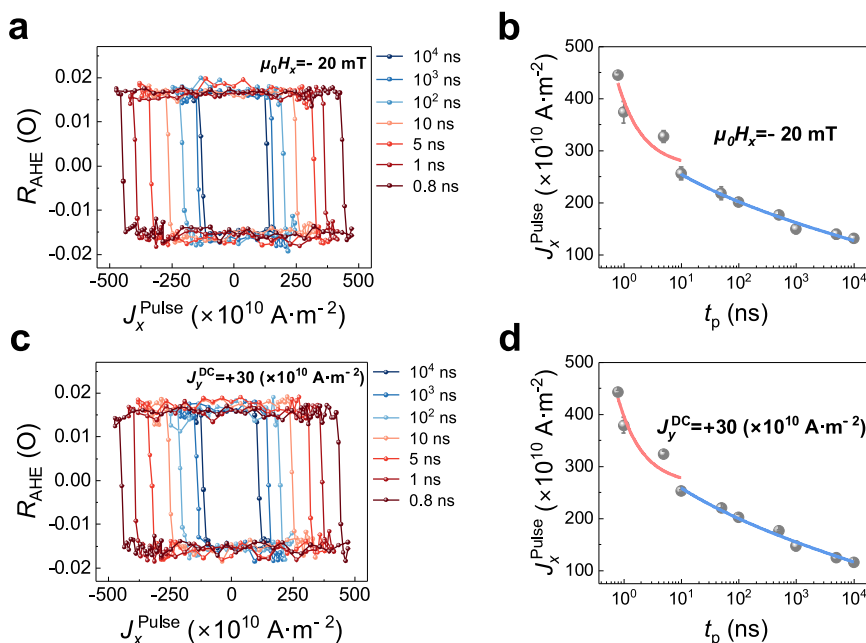


Fig. 3 | Field-assisted and field-free switching with variable pulse width. **a** Magnetic field-assisted SOT magnetization switching under an external magnetic field of $\mu_0 H_x = -20 \text{ mT}$ and pulse width of J_x^{pulse} ranging from 0.8 ns to 10 μs . **b** Pulse width-dependent critical current density for the magnetic field-assisted switching. **c** Field-free SOT magnetization switching under $J_y^{\text{dc}} = 30 \times 10^{10} \text{ A} \cdot \text{m}^{-2}$

and pulse width of J_x^{pulse} ranging from 0.8 ns to 10 μs . **d** Pulse width-dependent critical current density for the field-free switching. In **b**, **d**, the symbols are the experimental data, and the curves are the fittings with the formula detailed in the text.

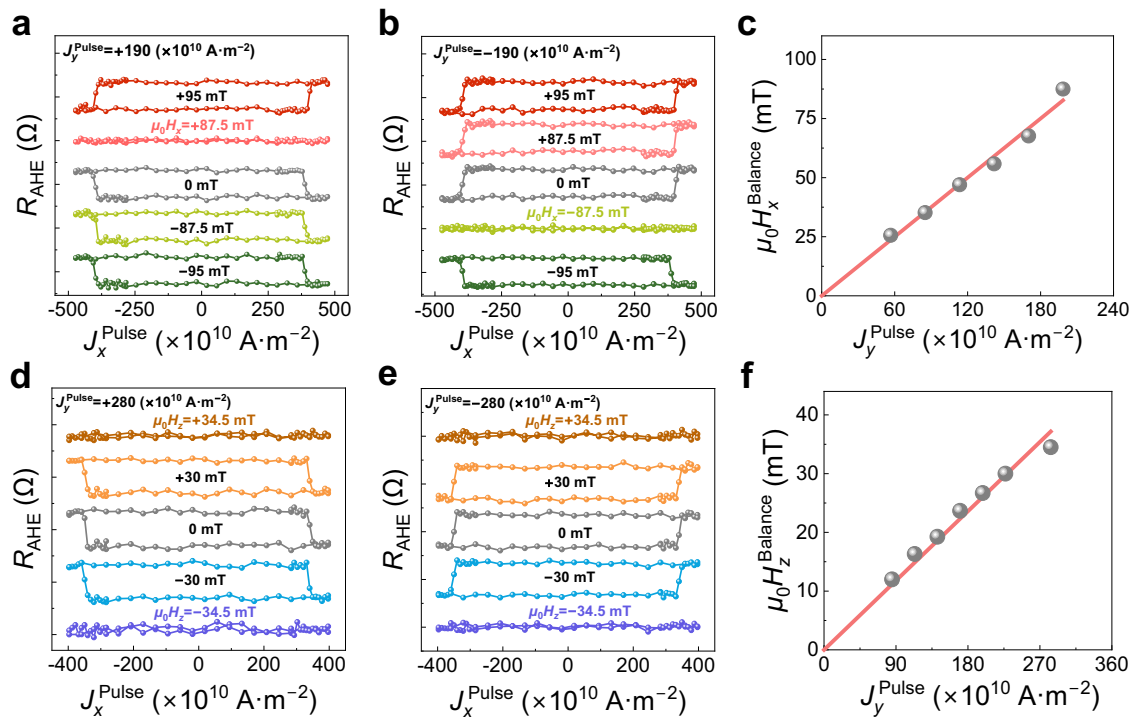


Fig. 4 | Magnetic-field immunity test. **a, b** Dual currents induced magnetization switching behavior with a fixed current of $J_y^{Pulse} = \pm 190 \times 10^{10} \text{ A} \cdot \text{m}^{-2}$ under different $\mu_0 H_x$. The switching exhibits magnetic-field immunity, with a balanced field of $\sim 87.5 \text{ mT}$. **d, e** Dual currents induced magnetization switching behavior with a

constant current of $J_y^{Pulse} = \pm 280 \times 10^{10} \text{ A} \cdot \text{m}^{-2}$ under different $\mu_0 H_z$. The balance field is $\sim 34.5 \text{ mT}$. **c, f** Dependence of the balance fields along the x/z -directions on J_y^{Pulse} , respectively.

direction of J_y^{Pulse} (Fig. 4b). All the results are consistent with those presented for DC current J_y^{DC} (Fig. 2). Overall, we find that the deterministic switching can be achieved when the duration of J_y^{Pulse} covers the falling edge of J_x^{Pulse} . To further support this conclusion, the raw double-pulse waveforms and the switching results under different pulse widths and delays are provided in Supplementary Note 7. In addition, we also studied magnetization switching with two synchronous pulses and a bending current. No deterministic switching was observed in either case, as shown in Supplementary Note 8.

The immunity of information processing and storage to external perturbation is important for maintaining their functionality, especially during read/write operations. One of the main concerns in magnetic storage techniques is magnetic-field immunity. Thus, both field-free switching and robust switching with magnetic field immunity are prerequisites for commercial application of SOT-MRAM. Although various field-free switching of perpendicular magnetization has been demonstrated, the switching polarity in most studies can be influenced by a small in-plane magnetic field^{28,29,33,38,40,41}. The magnetic immunity with respect to the perpendicular magnetic field has not been discussed. In this work, we study the robustness of SOT-switching under magnetic fields along all directions. Figures 4a, b present the switching curves under different external field $\mu_0 H_x$ applied along the x -direction. We find the deterministic switching disappears at $\mu_0 H_x \approx \pm 87.5 \text{ mT}$, which is defined as the balance magnetic field $\mu_0 H_x^{Balance}$ for $J_y^{Pulse} = \pm 190 \times 10^{10} \text{ A} \cdot \text{m}^{-2}$. Further increasing the field to $\mu_0 H_x \approx \pm 95 \text{ mT}$, the magnetization switching polarity is dominated by the external field and is opposite to the zero-field case. We find that the $\mu_0 H_x^{Balance}$ scales linearly with current density J_y^{Pulse} (Fig. 4c). This can be understood as the effective magnetic field originates from the J_y -induced SOT.

Similar measurements are also carried out under different $\mu_0 H_y$ and $\mu_0 H_z$. We find that the switching curves remain unaltered for the $\mu_0 H_y$ up to 87.5 mT (Supplementary Note 9). In the investigations of

magnetic immunity under $\mu_0 H_z$, the deterministic switching disappears at $\mu_0 H_z^{Balance} \approx \pm 34.5 \text{ mT}$ for $J_y^{Pulse} = \pm 280 \times 10^{10} \text{ A} \cdot \text{m}^{-2}$ (Fig. 4d, e). Similar to the case of $\mu_0 H_x^{Balance}$, $\mu_0 H_z^{Balance}$ also exhibits a linear dependence with J_y^{Pulse} (Fig. 4f). The magnetic immunity of SOT-switching shows some differences between $\mu_0 H_x$ and $\mu_0 H_z$. This can be understood as follows. Firstly, the scaling factors between the effective field and the current density J_y are different under $\mu_0 H_x$ and $\mu_0 H_z$. This is due to the different equilibrium directions of the magnetization and the switching trajectories back to the out-of-plane direction, which are determined by the total torques exerted by the spin current, the external magnetic field, the anisotropy field, and the demagnetization field. Secondly, the $\mu_0 H_x^{Balance}$ scales linearly with current density as long as the magnetic field is smaller than the perpendicular anisotropy field. The magnetization can switch back to the out-of-plane direction after the current is removed. On the contrary, $\mu_0 H_z^{Balance}$ is restricted by the coercivity of the Co layer, which is expected to be smaller than 40 mT in our device as the current pulse induced heating decreases the coercivity from the value of $\sim 40 \text{ mT}$ for the case of without heating (Fig. 1d). Thus, magnetic field larger than $\mu_0 H_z^{Balance}$ reverses the switching direction, while magnetic field larger than $\mu_0 H_z^{Balance}$ suppresses switching.

Overall, our device exhibits magnetic immunity above 30 mT across all magnetic field directions. This capability is adequate for various harsh environments in industrial, military and space applications⁴⁷. Moreover, magnetic immunity can be further enhanced by increasing the magnetic anisotropy of the ferromagnetic layer. Therefore, we demonstrate, for the first time, a field-free SOT switching of perpendicular magnetization that also exhibits high magnetic immunity along all directions. In the current-induced magnetization switching, a relatively large current density was applied to ensure sufficient SOT. This may raise a concern regarding possible Joule-heating-induced thermal effects. However, the temperature rise in the device remains rather limited (Supplementary Note 10).

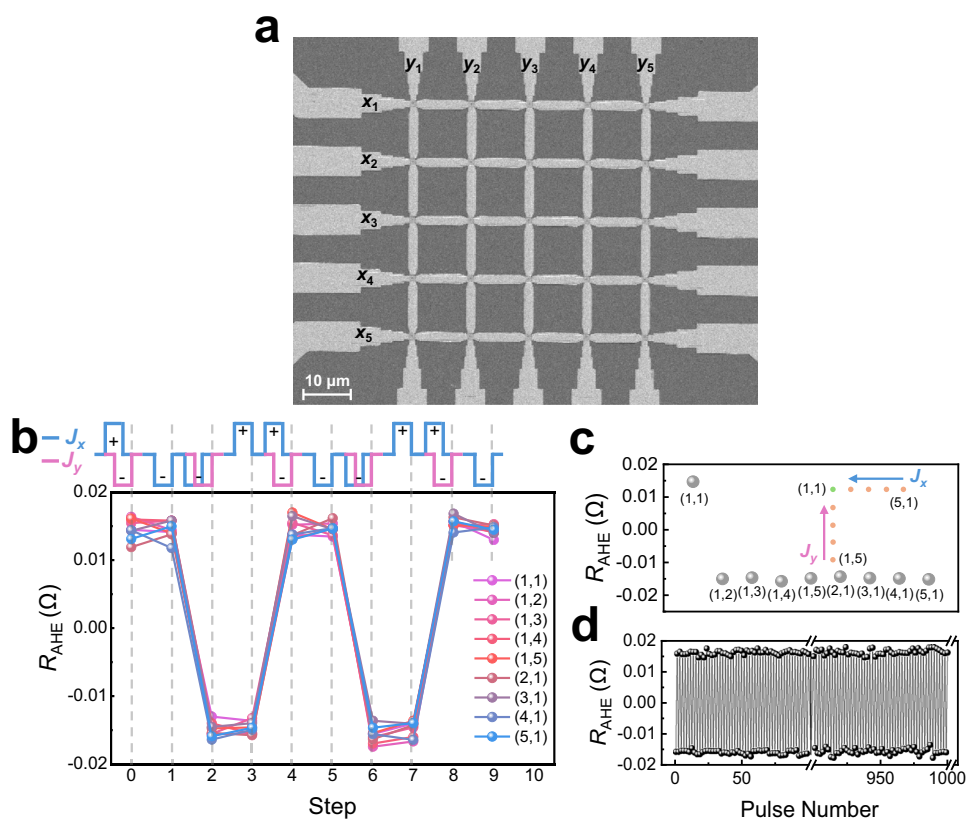


Fig. 5 | Test on 5×5 memory array. **a** SEM image of a 5×5 memory array. **b** The electrical read/write operations of the nine cells marked by the corresponding coordinates (x_i, y_i) in the array using the dual-current approach. The upper inset illustrates the applied current pulse sequences over time, with

$|J_x^{\text{pulse}}| = 90 \times 10^{10} \text{ A} \cdot \text{m}^{-2}$, $|J_y^{\text{pulse}}| = 90 \times 10^{10} \text{ A} \cdot \text{m}^{-2}$, $t_x = 10 \mu\text{s}$ and $t_y = 10 \mu\text{s}$. **c** Switching without influencing its neighbors occurred at the (x_i, y_i) cell with current pulses flowing along the horizontal line x_i and vertical line y_i . **d** Write endurance check which indicates no discernible degradation over 1000 switching.

We further demonstrate the random reading/writing operations in a cross-point array with 5×5 memory cells, mimicking the application in the SOT-MRAM. Figure 5a presents the typical SEM images of the 5×5 array. The channel width is 800 nm, and the Co disk diameter is 400 nm, similar to what is shown in Fig. 1c. A pair of horizontal line (x_i) and vertical line (y_j) act as both the writing and reading channels for the unit (x_i, y_j) . During the writing operation, two charge currents flow along x_i and y_j , respectively. Only the Co disk at the cross-point denoted as (x_i, y_j) switches accordingly, while the others remain unchanged due to insufficient torques acting on them. And in the reading operation, a small charge current flows along x_i , where the voltage along y_j is detected to monitor the magnetization direction of the disk (x_i, y_j) . Due to the limited number of cells in the array, the shunting effect during read and write operations is relatively weak⁴⁴. Figure 5b presents the electrical read/write operations of the nine cells marked by the corresponding coordinates using the dual-current approach. The inset illustrates the applied current pulse sequences over time, with $|J_x^{\text{pulse}}| = 90 \times 10^{10} \text{ A} \cdot \text{m}^{-2}$, $|J_y^{\text{pulse}}| = 90 \times 10^{10} \text{ A} \cdot \text{m}^{-2}$, $t_x = 10 \mu\text{s}$ and $t_y = 10 \mu\text{s}$. For instance, after initially magnetizing the device with a magnetic field along the z-direction, the unit (x_1, y_1) switches under current pulses J_x^{pulse} flows along x_1 and J_y^{pulse} flows along y_1 without influencing the other cells (Fig. 5c). The independent control of other cells in the array was also verified, as shown in Supplementary Note 11. The switching polarity of the target cell is determined by the combination of the directions of J_x^{pulse} and J_y^{pulse} , reversing either current direction changes the final state of magnetization. The current-induced switching behavior is consistent for all nine cells, as illustrated by different-colored AHE curves (Fig. 5b). Furthermore, the devices

exhibit repeated switching for more than 1000 pulses without errors, indicating high reliability (Fig. 5d).

Discussion

Although the AHE used for reading the information presented here is relatively small, given the high signal-to-noise ratio, our method shows a straightforward and reliable reading/writing operation with a pronounced on/off difference. This can be further improved by using selected materials with a large anomalous Hall angle, such as GdPtBi ²² and $\text{Co}_3\text{Sn}_2\text{S}_2$ ⁵³. In addition, our method is also compatible with practical SOT-MRAM applications. We propose a novel architecture for the SOT-MRAM with dual currents (Supplementary Note 12). This architecture is expected to achieve a higher cell density than conventional three-terminal SOT-MRAM while requiring significantly fewer transistors. It also alleviates the issues of MTJ breakdown and slow incubation in the STT-MRAM, as the reading and writing current follow different paths.

In summary, we have experimentally demonstrated ultra-fast, deterministic switching of perpendicular magnetization using dual orthogonal currents. The switching occurs not only without the assistance of an external field, but is also robust under a perturbing magnetic field of over 30 mT along all directions. The high magnetic immunity is adequate for various harsh environments in industrial, military, and space applications. Moreover, random read/write operations have been demonstrated in a cross-point array with 5×5 memory cells. As the spin currents are generated from the conventional spin Hall effect in a heavy metal, this approach is compatible with CMOS technology. Additionally, we have proposed a novel

SOT-MRAM architecture with dual charge currents. This architecture features field-free perpendicular magnetization switching, fast read/write operations, significant endurance, high immunity against external field perturbations, and compatibility with CMOS technology, casting strong potential for the next generation of SOT-MRAM.

Methods

Sample preparation

Ta(1)/Pt(6)/Co(1.2)/Ta(3) multilayers are deposited on high-resistivity silicon substrates at room temperature via a home-designed magnetron sputtering (manufactured by Temp Nanjing Industrial Technology). The numbers in parentheses are the corresponding thicknesses in nanometers. The base pressure within the chamber is below 5.0×10^{-8} Torr. All metallic layers are deposited utilizing a DC power supply with an Ar pressure of 3 mTorr and a flow rate of 30 sccm. The films are patterned into standard crossbars with a circular ferromagnet disk using e-beam lithography followed by ion milling. The crossbar was first covered with Ti(5)/Au(25), and then connected with electrodes prepared using Ti(5)/Au(120).

Device measurements

SOT-switching measurements are conducted by applying a single charge current pulse or dual orthogonal charge current pulses with different durations, via a PG-1072 pulse generator. As the impedance of the device $Z_0 \sim 170 \Omega$ is higher than that of the coaxial cable $R = 50 \Omega$, the amplitude of current pulse is almost doubled, following $I(R) = 2Z_0/(Z_0 + R)$. After each pulse injection, the anomalous Hall resistance R_{AHE} is measured using a Keithley 6221 current source and 2182A nano-voltmeter to probe the magnetization direction of the Co layer. Magnetic fields of varying magnitude are applied along different directions to perform the field-assisted SOT switching and to investigate the magnetic immunity of magnetization switching.

Data availability

The data that support the results of this study are available from the corresponding authors upon reasonable request. Source data are provided with this paper.

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Author contributions

B.M. and H.D. conceived and supervised the project. J.S., J.C. and Y.Z. carried out the experiments and analyzed the data. J.S., B.M. and H.D.

prepared the manuscript. M.Y., C.F. and X.Z. provided crucial assistance in revising the manuscript. J.S., T.J. and X.Y. built the ultrafast electrical testing experimental platform. J.S., J.C., Y.Z., Z.Z., M.Y., C.F., H.N., T.J., Z.C., X.Y., L.Y., M.J., J.M., L.S., G.C., X.Z., B.M. and H.D. discussed and interpreted the results. All authors commented on the manuscript.

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Competing interests

The authors declare no competing interests.

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