

RESEARCH ARTICLE | MARCH 14 2024

Field-free switching in perpendicular Ta/CoFeB/MgO multilayers achieved by annealing temperature gradient

Shuanghai Wang ; Xingze Dai ; Kun He; Jin Wang; Xiaolong Zhang; Qixun Guo ; Guanqun Feng ; Yongkang Xu; Yafeng Deng ; Ruobai Liu ; Jun Du ; Yong-Lei Wang ; Chao Wang ; Yongbing Xu; Liang He  



Appl. Phys. Lett. 124, 112415 (2024)

<https://doi.org/10.1063/5.0192575>



Articles You May Be Interested In

Efficient spin-orbit torque switching in perpendicularly magnetized CoFeB facilitated by Fe_2O_3 underlayer

Appl. Phys. Lett. (July 2023)

Current-induced spin-orbit torque switching of perpendicularly magnetized Hf|CoFeB|MgO and Hf|CoFeB|TaO_x structures

Appl. Phys. Lett. (April 2015)

Effect of the oxide layer on current-induced spin-orbit torques in Hf|CoFeB|MgO and Hf|CoFeB|TaO_x structures

Appl. Phys. Lett. (January 2015)



Nanotechnology & Materials Science



Optics & Photonics



Impedance Analysis



Scanning Probe Microscopy



Sensors



Failure Analysis & Semiconductors

Unlock the Full Spectrum.
From DC to 8.5 GHz.



Zurich Instruments

Find out more

Field-free switching in perpendicular Ta/CoFeB/MgO multilayers achieved by annealing temperature gradient

Cite as: Appl. Phys. Lett. **124**, 112415 (2024); doi: [10.1063/5.0192575](https://doi.org/10.1063/5.0192575)

Submitted: 20 December 2023 · Accepted: 2 March 2024 ·

Published Online: 14 March 2024



Shuanghai Wang,¹ Xingze Dai,¹ Kun He,¹ Jin Wang,¹ Xiaolong Zhang,¹ Qixun Guo,² Guanqun Feng,¹ Yongkang Xu,¹ Yafeng Deng,¹ Ruobai Liu,³ Jun Du,³ Yong-Lei Wang,⁴ Chao Wang,⁵ Yongbing Xu,¹ and Liang He^{1,a)}

AFFILIATIONS

¹State Key Laboratory of Spintronics Devices and Technologies, School of Electronic Science and Engineering, Nanjing University, Nanjing 210023, China

²Ji Hua Laboratory, Foshan 528000, China

³National Laboratory of Solid State Microstructures and Department of Physics, Nanjing University, Nanjing 210093, China

⁴Research Institute of Superconductor Electronics, School of Electronic Science and Engineering, Nanjing University, Nanjing 210023, China

⁵Institute of Nanosurface Science and Engineering, College of Mechatronics and Control Engineering, Shenzhen University, Shenzhen 518060, China

^{a)}Author to whom correspondence should be addressed: heliang@nju.edu.cn

ABSTRACT

Current flowing through heavy metals generates spin current by the spin Hall effect (SHE), and spin current exerts a torque on the adjacent magnetic layer, thereby switching the magnetization direction of the magnetic layer. Normally, an external magnetic field must be used to break symmetry in the response to the SHE torque, to realize deterministic switching. However, the presence of magnetic fields increases the difficulty in integrating spintronic devices with complementary metal-oxide-semiconductor. Thus, field-free spin-orbit torque switching has been a research hotspot. Here, symmetry-breaking has been realized by tilting the sample during the annealing process, resulting in a non-uniform diffusion of Ta atoms in the samples along the temperature gradient (x -direction), which was confirmed by transmission electron microscope mapping. As a result, the sample has demonstrated deterministic switching, in the absence of an external magnetic field, with a switching ratio of up to 88% and the critical current density of 1.5×10^7 A/cm². Tilting annealing is a simple approach to achieve field-free switching.

Published under an exclusive license by AIP Publishing. <https://doi.org/10.1063/5.0192575>

In the writing process of spin-orbit torque (SOT)-based magnetic random-access memory (SOT-MRAM), the large charge current only passes through the heavy metal (HM) layer instead of the barrier layer. This reduces the risk of breaking down the barrier layer and thus increases the operating lifetime of the device.^{1–8} SOT mainly has two mechanisms, the spin Hall effect (SHE) and the Rashba effect. In the SHE, when a current flows through a heavy metal (HM) layer, due to spin-orbit coupling, it generates a spin current that is transferred to the ferromagnetic (FM) layer and exerts a spin transfer torque on its magnetization.^{9–12} However, the magnetic moment cannot undergo deterministic switching due to the symmetry of the spatial inversion. At the beginning, the symmetry was broken by applying an external

magnetic field to achieve a deterministic switching.^{13,14} However, the presence of this magnetic field does not meet the requirement for high-density spintronic devices. Thus, field-free SOT switching is highly desired.

In FM/HM or ferrimagnetic (FIM)/HM heterostructures, many methods have been attempted to break the symmetry and field-free switching has been achieved, including interlayer coupling,¹⁵ concentration gradient,¹⁶ exchange bias,^{17,18} crystal structure asymmetry,^{19,20} tilted anisotropy,^{21,22} wedge-shaped growth of heavy metals^{23,24} synthetic antiferromagnets,²⁵ perpendicular spins,²⁶ asymmetric device geometry,²⁷ etc. In this study, by generating a temperature gradient during the annealing process, field-free switching has been realized in

a CoFeB/MgO structure. It should be noted that it is difficult to apply the temperature gradient method to large-scale fabrication.

In this study, A Ta (5)/CoFeB (1)/MgO (2)/Ta (2) (thickness in nm) structure was deposited through sputtering and annealed at 280 °C for 30 min with a tilting stage. After annealing, crossbar devices have been fabricated and measured. All of them have shown deterministic field-free switching, with a switching ratio as high as 88%. This field-free switching was attributed to the non-uniformly diffused of Ta atoms into the CoFeB layer due to the temperature gradient, which caused a small spin current gradient along the x -direction. This concentration gradient breaks the symmetry in the response to the SHE torque and leads to field-free switching.

Ta/CoFeB/MgO/Ta multilayers were deposited on Si/SiO₂ substrates by magnetron sputtering system (SSI UHV-sputter) with a base pressure of 3×10^{-7} Torr. The size of the substrate is 1×1 cm², and the diameters of all the targets are 50.8 mm. The purity of Ta, CoFeB (4:4:2), and MgO (1:1) target is 99.95%. The sputtering gas used is 99.999% Ar for all the materials. For metal deposition, the pressure is kept at 6 mTorr and the DC power is kept at 10 W. For MgO deposition, the pressure is 10 mTorr and the RF power is 50 W. The deposition rates are 0.16, 0.12, 0.07 Å/s for Ta, CoFeB, and MgO layers, respectively. During deposition, the substrates were kept at room temperature.

After the deposition, the samples were annealed at 280 °C for 30 mins in the sputter chamber, using two mounting methods. The inset of Fig. 1(a) shows a schematic diagram of the normal mounted sample A, which means the whole sample has undergone the same annealing temperature. On the other hand, as shown in the inset of Fig. 1(b), sample B has only one end touched the heater, resulting in a temperature gradient of ~ 0.76 °C/mm along the x -direction. After annealing, the magnetism of the samples was measured using a magneto-optical Kerr effect (MOKE) system and a vibrating sample magnetometer (VSM). Then, three devices of B1 (in the higher temperature end), B2 (in the middle temperature), and B3 (in the lower temperature end)

along the x -direction have been fabricated by a standard photolithography technique. For current-induced magnetization switching measurements, a pulsed current I_{pulse} with a width of 0.1 ms is applied along the long side (x -direction) of the devices. After the pulse, an DC excitation current I_{DC} (200 μ A) was output to the current path and the Hall voltage V_{xy} was measured by a nanovoltmeter (Keithley 2182A).

Figures 1(a) and 1(b) exhibit normalized magnetization vs magnetic field (M-H) hysteresis loops of the normal mounted sample A and the tilted sample B, after being annealed at 280 °C for 30 min. The green circles and red triangles represent the hysteresis loops with the magnetic fields applied perpendicular or parallel to the film surface, respectively. Both samples exhibit an out-of-plane easy axis. At the same time, Figs. 1(c) and 1(d) demonstrate the normalized polar magneto-optical Kerr effect (P-MOKE) loops. The squareness of the P-MOKE loops indicates that samples A and B maintain good perpendicular magnetic anisotropy (PMA). The results obtained by VSM and P-MOKE are consistent.

After annealing, the samples were fabricated into a crossbar device using standard photolithography and ion beam etching processes. The width of the current channel is 20 μ m. The current and voltage electrodes are made of a 15-nm Ti layer and a 35-nm Au layer, as shown in the inset of Fig. 2(a). Figures 2(a) and 2(b) present the anomalous Hall effect (AHE) curve and the SOT switching curve of A, respectively. The AHE curve in Fig. 2(a) displays a good rectangularity, indicating that A still possesses good PMA after microfabrication. Figures 2(b) and S1 reveal the SOT switching curves with different magnetic fields. It is clear that the magnetic moment of A cannot be switched without the external magnetic field. This is consistent with other research works.^{28–30}

Figures 2(c) and 2(d) show the AHE loop and the SOT switching curve of B1, respectively. The AHE curve of B1 exhibits similar results as A, indicating that B1 also has good PMA. More importantly, the SOT switching curve demonstrates that B1 has achieved field-free switching, with the switching ratio of as high as 88% compared to the

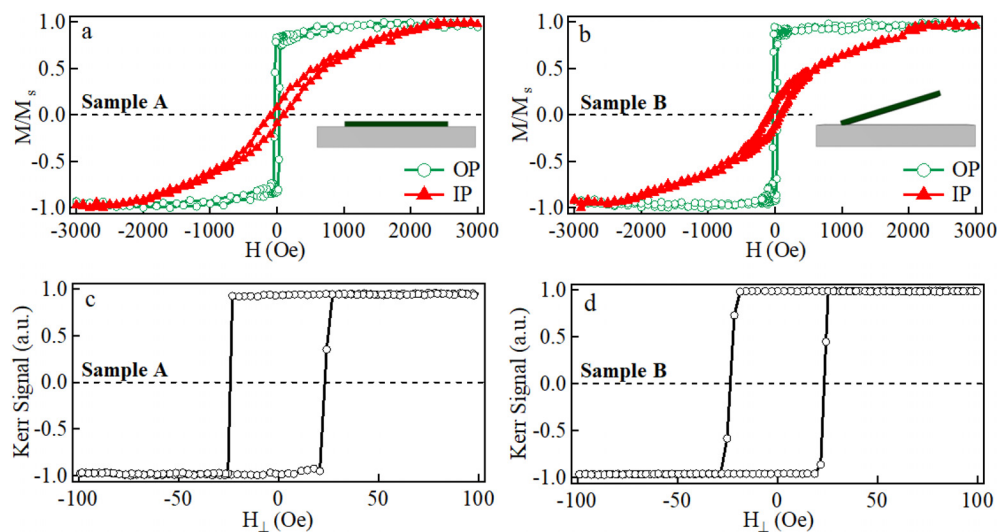


FIG. 1. Hysteresis loops measured on different magnetic fields for sample A (a) and sample B (b). The mounting methods of sample A and sample B are shown in the insets of (a) and (b), respectively. P-MOKE hysteresis loops of sample A (c) and sample B (d). It is evidenced that both sample A and sample B possess PMA after annealing.

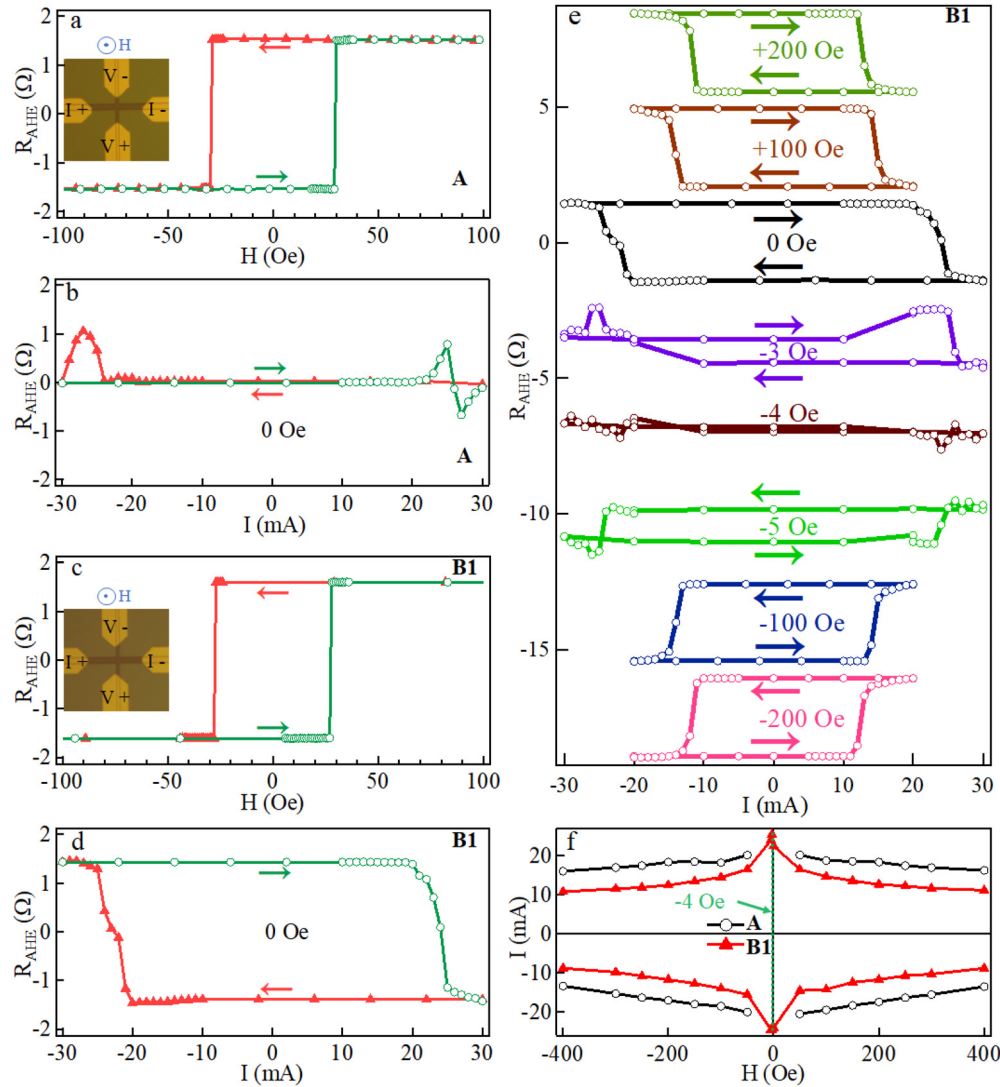


FIG. 2. Magnetic and SOT properties for the A and B1. Representative out-of-plane hysteresis loops as obtained by anomalous Hall voltage measurements of A (a) and B1 (c). In-plane (x -direction) pulse-current-induced perpendicular magnetization switching without external magnetic field for A (b) and B1 (d). (e) Current-induced magnetization switching in the B1, under various in-plane magnetic fields H_x ranging from -200 Oe to 200 Oe. (f) Switching phase diagram of A and B1. Under the same magnetic field, the critical switching current of B1 is lower than that of A, and field-free switching can be achieved in B1.

ΔR of AHE. The critical current density J_c of B1 at zero magnetic field is 1.5×10^7 A/cm².

Figure 2(e) shows the switching loops of B1 under different in-plane fields H_x , parallel to the current. The SOT switching loops are clockwise under a positive magnetic field and counter-clockwise under a negative magnetic field. We have noticed that the B1 does not switch when the magnetic field is -4 Oe, suggesting that the built-in field is $+4$ Oe. We have conducted MOKE imaging tests on the B1 sample at -50 , 0 , and 50 Oe, as shown in Fig. S2. It can be seen that the magnetization can be switched by the current, even when the applied external magnetic field is zero. Also, the switching mechanism can be concluded as the domain wall movement.

Figure 2(f) exhibits the switching phase diagram of A and B1. Under the same magnetic field, the critical switching current of B1 is much lower than that of A. More importantly, B1 demonstrates a field-free switching and shifts the center of the diagram to the negative field direction by -4 Oe, as indicated by the dotted green line.

The AHE and SOT switching curves of B2 and B3 are demonstrated in Figs. S3(b) and S3(c). AHE curves of all the samples exhibit good rectangularity, implying that all samples have good PMA. At the same time, the corresponding SOT curves demonstrate field-free switching, with the switching ratio above 80%. Samples of the current channel perpendicular to the temperature field direction have been obtained. From Figs. S4(a) and S4(b), we can see that C (middle temperature) has good PMA. The SOT switching curve of the sample at

zero magnetic field shows that the sample cannot fully reverse, only a small portion. This indicates that only when the sample's current direction is parallel to the temperature field direction, can the sample achieve field-free switching.

To investigate the damping like torque (DLT) of SOT induced spin current, a second harmonic method has been adopted, as shown in Fig. S5. The magnetic field is applied along the x -direction, with a small inclination angle (φ_H) to the film surface to prevent the formation of multiple domains. An AC with a frequency of 133 Hz is applied along the x -direction. Simultaneously, the first (V_ω) and secondary ($V_{2\omega}$) harmonic signals are acquired through a lock-in amplifier of OE1022D. Figures 3(a) and 3(b) show V_ω and $V_{2\omega}$ harmonic Hall voltages as a function of magnetic field H_x with an AC of 1 mA. Using the following formula,^{31,32}

$$H_L = \frac{\partial V_{2\omega}}{\partial H_x} \bigg/ \frac{\partial^2 V_\omega}{\partial H_x^2}. \quad (1)$$

The longitudinal effective field (H_L) induced by SOT can be quantitatively extracted. The damping-like effective field H_D generated by the current is based on the following formula:³⁴

$$H_D = -2 \frac{H_L + 2\xi H_L}{1 - 4\xi^2}. \quad (2)$$

ξ is the ratio of planar Hall resistance to anomalous Hall resistance. In the Ta/CoFeB/MgO/Ta system, planar Hall values are very small and are often neglected.³³ So, H_D can be simplified as $-2H_L$. The extracted H_D are plotted vs I_{AC} for both devices, as shown in Figs. 3(c) and 3(d). Based on linear fitting, the damping-like torque efficiency (β_D), defined by the damping-like efficient field per charge current density, is $2.77 \times 10^{-6} \text{ Oe}/(\text{A}/\text{cm}^2)$ for A and $3.06 \times 10^{-6} \text{ Oe}/(\text{A}/\text{cm}^2)$ for B1, respectively. The difference in β_D is not significant. The spin Hall angle of Ta can also be extracted using the following equation:

$$\theta_{SH} = 2eM_s t_{\text{CoFeB}} \beta_D / \hbar.$$

Here, e is the electron charge, M_s is the saturation magnetization of CoFeB, t_{CoFeB} is the thickness of CoFeB, and $\hbar$ is the reduced Planck

constant. Thus, θ_{SH} of Ta is 0.07. This is consistent with other research findings.^{34,35}

Figure 4(a) shows the simulated temperature distributions for tilted sample B during the annealing process. The highest temperature is 279.6°C at the contacted end, and the lowest temperature is 272°C at the free end. The average temperature gradient is $0.76^\circ\text{C}/\text{mm}$. The derivative of the temperature curve is shown in Fig. 4(b), demonstrating a linear dependence. This can be understood as that since the sample is annealed in a vacuum chamber, the only heat lost at the free end is the radiation to the chamber. The radiation power is proportional to the sample temperature as well as the sample surface area. The surface area is linearly proportional to the distance to the cold end. Thus, the closer to the free end, the smaller the surface area is. As shown in Fig. 4(b) illustration, when current passes through the sample in the x -direction, the arrows (in orange and purple) indicate the polarized electrons moving along the z -direction (indicated by the dashed black arrows), which generates a spin current (J_s) along the z -direction. The size of the arrows represents the amounts of polarized electrons due to the concentration gradient of Ta. Thus, there exist a spin current gradient along the x -direction.

As shown in Fig. 4(d), from the energy dispersive spectroscopy (EDS) mapping of Ta by transmission electron microscope (TEM), the diffusion in the high-temperature zone is stronger, while the diffusion in the low-temperature zone is weaker. Figure S6 shows the intensity profiles of Ta extracted from each temperature region in Fig. 4(d). The amount of Ta in the CoFeB region is significantly different, with B1 being the highest and B3 being the lowest. Figure 4(c) shows the structural diagram of Ta/CoFeB/MgO/Ta after tilted annealing, indicating that Ta in the buffer layer diffuses into the CoFeB layer non-uniformly due to the temperature gradient, forming a certain concentration gradient along the temperature gradient direction (x -direction), as indicated by blue balls in the insets. The concentration gradient of Ta can produce a gradient of spin current [red arrows in Fig. 4(c)], when electron current flows through the CoFeB layer, as discussed in the supplementary material, Fig. S7. The concentration gradient produces a spin current gradient and induces a built-in in-plane field. This field breaks the spatial symmetry in the x -direction, resulting in a deterministic

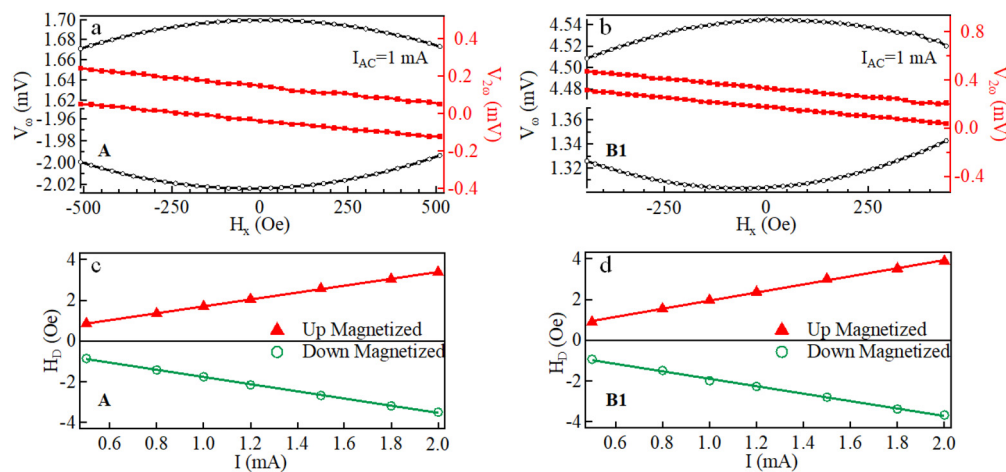


FIG. 3. Harmonic Hall measurements of the Hall-bar devices. The V_ω and $V_{2\omega}$ harmonic Hall voltages as a function of magnetic field H_x for A (a) and B1 (b). Current dependence of damping-like effective field (H_D) of A (c) and B1 (d), where the red and green linear lines are the fitted curves.

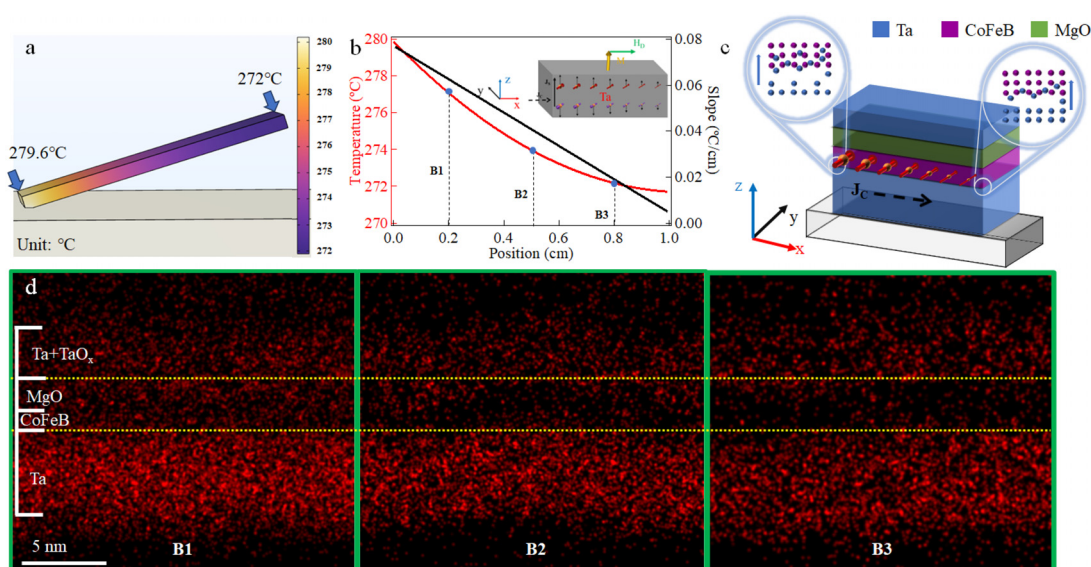


FIG. 4. Schematic diagram of tilted annealing simulation and TEM analysis. (a) The simulated temperature distribution during tilted annealing. (b) Position dependent temperature (red curve) and the derivation of it (black curve). (c) The Schematic of Ta/CoFeB/MgO/Ta after tilted annealing, spin current gradient along the x -direction, and non-uniform diffusion of Ta in the CoFeB layer. (d) EDS mapping of Ta of the sample B series.

switching of the magnetic moment in the absence of an external magnetic field. This is consistent with the literature reports.³⁶

In summary, we have demonstrated field-free switching in a Ta/CoFeB/MgO/Ta structure with PMA by the tilted annealing method. The switching ratio has achieved as high as 88%, with a critical current density of 1.5×10^7 A/cm². Furthermore, the critical current of tilted annealed sample decreased by 22.8% compared to A under the same magnetic field. This field-free switching has been attributed to different amounts of diffused heavy metal Ta into the CoFeB layer due to the temperature gradient. The concentration gradient produces a spin current gradient and induces a built-in in-plane field, breaks the symmetry in the x -direction, and results in the field-free switching. Our results provide a very simple and easy to be adopted method to achieve field-free switching in the conventional SOT devices.

See the supplementary material for the anomalous Hall effect and SOT switching of the samples A, B, and C; the schematic diagram of harmonic Hall measurements; the intensity of Ta extracted from each temperature region in sample B; and the switching phase diagram of B1 and B3.

This work was supported by the National Natural Science Foundation of China (No. 12241403), the National Natural Science Foundation of China (Grant Nos. T2394473 and T2394470), and the Natural Science Foundation of Jiangsu Province of China (No. BK20140054).

AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Shuanghai Wang: Conceptualization (equal); Data curation (equal); Investigation (equal); Writing – original draft (equal); Writing – review & editing (equal). **Xingze Dai:** Investigation (equal). **Kun He:** Investigation (equal). **Jin Wang:** Investigation (equal). **Xiaolong Zhang:** Investigation (equal). **Qixun Guo:** Investigation (equal). **Guanqun Feng:** Investigation (equal). **Yongkang Xu:** Investigation (equal). **Yafeng Deng:** Investigation (equal). **Ruobai Liu:** Investigation (equal). **Jun Du:** Resources (equal). **Yong-Lei Wang:** Resources (equal). **Chao Wang:** Resources (equal). **Yongbing Xu:** Resources (equal). **Liang He:** Funding acquisition (equal); Project administration (equal); Supervision (equal); Writing – review & editing (equal).

DATA AVAILABILITY

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

REFERENCES

- X. Qiu, Z. Shi, W. Fan, S. Zhou, and H. Yang, *Adv. Mater.* **30**(17), 1705699 (2018).
- X. Qiu, K. Narayanapillai, Y. Wu, P. Deorani, D.-H. Yang, W.-S. Noh, J.-H. Park, K.-J. Lee, H.-W. Lee, and H. Yang, *Nat. Nanotechnol.* **10**(3), 333–338 (2015).
- X. Han, X. Wang, C. Wan, G. Yu, and X. Lv, *Appl. Phys. Lett.* **118**(12), 120502 (2021).
- J.-M. Kim, D.-J. Kim, C.-Y. Cheon, K.-W. Moon, C. Kim, P. Cao Van, J.-R. Jeong, C. Hwang, K.-J. Lee, and B.-G. Park, *Nano Lett.* **20**(11), 7803–7810 (2020).
- Y. Cao, Y. Sheng, K. W. Edmonds, Y. Ji, H. Zheng, and K. Wang, *Adv. Mater.* **32**(19), 1907929 (2020).
- Y. Song, X. Zhao, W. Liu, L. Liu, S. Li, and Z. Zhang, *Appl. Phys. Lett.* **117**(23), 232408 (2020).

- ⁷H. Wu, A. Chen, P. Zhang, H. He, J. Nance, C. Guo, J. Sasaki, T. Shirokura, H. Pham N, B. Fang, S. A. Razavi, K. Wong, Y. Wen, Y. Ma, G. Yu, G. P. Carman, X. Han, X. Zhang, and K. L. Wang, *Nat. Commun.* **12**, 6251 (2021).
- ⁸I. S. Shin, W. J. Cho, E.-S. An, S. Park, H.-W. Jeong, J. Seong, W. J. Baek, S. Y. Park, D.-H. Yang, J. H. Seo, G. Y. Kim, M. N. Ali, S.-Y. Choi, H.-W. Lee, J. S. Kim, S. D. Kim, and G.-H. Lee, *Adv. Mater.* **34**(21), 2101730 (2022).
- ⁹A. Manchon, J. Železný, I. M. Miron, T. Jungwirth, J. Sinova, A. Thiaville, K. Garello, and P. Gambardella, *Rev. Mod. Phys.* **91**, 035004 (2019).
- ¹⁰H. Ju, X. Zhao, W. Liu, Y. Song, L. Liu, J. Ma, Y. Li, J. Wu, and Z. Zhang, *ACS Appl. Mater. Interfaces* **13**(51), 61742–61750 (2021).
- ¹¹L. Liu, J. H. Yu, R. González-Hernández, C. Li, J. Y. Deng, W. N. Lin, C. H. Zhou, T. J. Zhou, J. Jing, H. Wang, R. Guo, H. Y. Yoong, G. M. Chow, X. F. Han, B. Dupé, J. Železný, J. Sinova, and J. S. Chen, *Phys. Rev. B* **101**(22), 220402 (2020).
- ¹²B. Cui, H. Wu, D. Li, S. A. Razavi, D. Wu, K. L. Wong, M. Chang, M. Gao, Y. Zuo, L. Xi, and K. L. Wang, *ACS Appl. Mater. Interfaces* **11**(42), 39369–39375 (2019).
- ¹³C. Li, X. Xu, T. Zhang, Z. Zhu, Q. Liu, L. Song, Y. Wu, K. Meng, J. Chen, W. Wang, and Y. Jiang, *Appl. Phys. Lett.* **123**(5), 052404 (2023).
- ¹⁴C.-W. Peng, W.-B. Liao, T.-Y. Chen, and C.-F. Pai, *ACS Appl. Mater. Interfaces* **13**(13), 15950–15957 (2021).
- ¹⁵Y. C. Lau, D. Betto, K. Rode, J. M. D. Coey, and P. Stamenov, *Nat. Nanotechnol.* **11**, 758–762 (2016).
- ¹⁶Z. Zheng, Y. Zhang, V. Lopez-Dominguez, L. Sánchez-Tejerina, J. Shi, X. Feng, L. Chen, Z. Wang, Z. Zhang, K. Zhang, B. Hong, Y. Xu, Y. Zhang, M. Carpentieri, A. Fert, G. Finocchio, W. Zhao, and P. Khalili Amiri, *Nat. Commun.* **12**, 4555 (2021).
- ¹⁷S. Fukami, C. Zhang, S. DuttaGupta, A. Kurenkov, and H. Ohno, *Nat. Mater.* **15**, 535–541 (2016).
- ¹⁸Y.-W. Oh, S. H. Baek, Y. M. Kim, H. Y. Lee, K.-D. Lee, C.-G. Yang, E.-S. Park, K.-S. Lee, K.-W. Kim, G. Go, J.-R. Jeong, B.-C. Min, H.-W. Lee, K.-J. Lee, and B.-G. Park, *Nat. Nanotechnol.* **11**, 878–884 (2016).
- ¹⁹L. Liu, C. Zhou, X. Shu, C. Li, T. Zhao, W. Lin, J. Deng, Q. Xie, S. Chen, J. Zhou, R. Guo, H. Wang, J. Yu, S. Shi, P. Yang, S. Pennycook, A. Manchon, and J. Chen, *Nat. Nanotechnol.* **16**, 277–282 (2021).
- ²⁰L. Liu, C. Zhou, T. Zhao, B. Yao, J. Zhou, X. Shu, S. Chen, S. Shi, S. Xi, D. Lan, W. Lin, Q. Xie, L. Ren, Z. Luo, C. Sun, P. Yang, E.-J. Guo, Z. Dong, A. Manchon, and J. Chen, *Nat. Commun.* **13**, 3539 (2022).
- ²¹H.-J. Kim, K.-W. Moon, B. X. Tran, S. Yoon, C. Kim, S. Yang, J.-H. Ha, K. An, T.-S. Ju, J.-I. Hong, and C. Hwang, *Adv. Funct. Mater.* **32**, 2112561 (2022).
- ²²Y. Long, O. J. Lee, D. Bhowmik, D. Labanowski, J. Hong, J. Bokor, and S. Salahuddin, *Proc. Natl. Acad. Sci. U. S. A.* **112**, 10310–10315 (2015).
- ²³T.-Y. Chen, H.-I. Chan, W.-B. Liao, and C.-F. Pai, *Phys. Rev. Appl.* **10**(4), 044038 (2018).
- ²⁴A. Razavi, H. Wu, B. Dai, H. He, D. Wu, K. Wong, G. Yu, and K. L. Wang, *Appl. Phys. Lett.* **117**(18), 182403 (2020).
- ²⁵H. Fan, M. Jin, B. Wu, M. Wei, J. Wang, Z. Shao, C. Yu, J. Wen, H. Li, W. Li, and T. Zhou, *Appl. Phys. Lett.* **122**(26), 262404 (2023).
- ²⁶S. Hu, D.-F. Shao, H. Yang, C. Pan, Z. Fu, M. Tang, Y. Yang, W. Fan, S. Zhou, E. Y. Tsybal, and X. Qiu, *Nat. Commun.* **13**, 4447 (2022).
- ²⁷Q. Liu and L. Zhu, *Appl. Phys. Rev.* **9**, 041401 (2022).
- ²⁸S. K. Li, X. T. Zhao, W. Liu, Y. H. Song, L. Liu, X. G. Zhao, and Z. D. Zhang, *Appl. Phys. Lett.* **114**(8), 082402 (2019).
- ²⁹X. Zhao, Y. Liu, D. Zhu, M. Sall, X. Zhang, H. Ma, J. Langer, B. Ocker, S. Jaiswal, G. Jakob, M. Kläui, W. Zhao, and D. Ravelosona, *Appl. Phys. Lett.* **116**, 242401 (2020).
- ³⁰H. Wu, P. Zhang, P. Deng, Q. Lan, Q. Pan, S. A. Razavi, X. Che, L. Huang, B. Dai, K. Wong, X. Han, and K. L. Wang, *Phys. Rev. Lett.* **123**(20), 207205 (2019).
- ³¹J. Kim, J. Sinha, M. Hayashi, M. Yamanouchi, S. Fukami, T. Suzuki, S. Mitani, and H. Ohno, *Nat. Mater.* **12**, 240–245 (2013).
- ³²Y. Li, X. Zhao, W. Liu, J. Wu, L. Liu, Y. Song, J. Ma, and Z. Zhang, *Appl. Phys. Lett.* **123**(3), 032403 (2023).
- ³³W. L. Peng, J. Y. Zhang, G. N. Feng, X. L. Xu, C. Yang, Y. L. Jia, and G. H. Yu, *Appl. Phys. Lett.* **115**(9), 092402 (2019).
- ³⁴T.-Y. Tsai, T.-Y. Chen, C.-T. Wu, H.-I. Chan, and C.-F. Pai, *Sci. Rep.* **8**, 5613 (2018).
- ³⁵Z. Y. Li, X. Y. Lu, Z. Zhang, W. J. Li, T. T. Li, J. Zhou, Y. Yan, R. B. Liu, J. Du, R. H. Liu, X. R. Wang, Y. Li, L. He, J. Wu, R. Zhang, and Y. B. Xu, *Appl. Phys. Lett.* **123**, 042404 (2023).
- ³⁶S. Chen, J. Yu, Q. Xie, X. Zhang, W. Lin, L. Liu, Z. Jing, X. Shu, R. Guo, Z. Zhang, and J. Chen, *ACS Appl. Mater. Interfaces* **11**(33), 30446–30452 (2019).