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Critical current for field-free switching of the in-plane magnetization in the three-terminal magnetic tunnel junction

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Spin-orbit torque magnetic random-access memory (SOT-MRAM) has been a promising candidate for next-generation non-volatile memory, offering advantages such as energy efficiency, high speed, and scalability. The in-plane-magnetized three-terminal magnetic tunnel junctions (MTJs) are favored for SOT-MRAM due to their ease of fabrication and integration. These MTJs are classified into two categories: Type-y and Type-x devices. The former enables deterministic switching without an external magnetic field but has a long precession time, limiting the speed. The latter has a faster switching speed but requires an external magnetic field for deterministic switching. The use of the magnetic field increases the difficulties in chip integration. In order to balance field-free switching and high-speed writing in Type-x devices, two solutions have been developed and experimentally validated: (1) combining SOT and spin-transfer torque (STT) known as toggle spin torque (TST) [1], and (2) canting the easy-axis of MTJ to break symmetry [2]. While these two solutions show both practical feasibility and performance advantages, the derivation of the critical switching current remains challenging due to complicated multi-physics coupling. To date, no theoretical studies have addressed this problem, which makes it difficult to accurately predict device performance.

In this study, we propose a novel theoretical approach using the Routh-Hurwitz criterion to derive the critical switching current for the two kinds of Type-x devices. The derived formulas provide clear physical insights and align well with the numerical simulations. Our findings offer valuable guidance for optimization and contribute to the development of field-free, energy-efficient, and high-speed SOT-MRAM.

Theoretical derivation. We begin by analyzing a Type-x device of TST configuration. As shown in Figure 1(a), two currents are applied: one to the SOT channel to induce SOT and the other to the MTJ to generate STT. In this case, the magnetization dynamics are described by the modified Landau-Lifshitz-Gilbert (LLG) equation:

$$\frac{\partial \boldsymbol{m}}{\partial t} = -\gamma \boldsymbol{m}\times\boldsymbol{H}_{\rm eff} + \alpha \boldsymbol{m}\times\frac{\partial \boldsymbol{m}}{\partial t} - \gamma H_{\rm SOT}\boldsymbol{m}\times(\boldsymbol{\sigma}\times\boldsymbol{m}) - \gamma H_{\rm STT}\boldsymbol{m}\times(\boldsymbol{m}_p\times\boldsymbol{m}), \tag{1}$$

where γ and α are the gyromagnetic ratio and the Gilbert damping constant, respectively. $\boldsymbol{m} = \boldsymbol{M}/M_s$ denotes the normalized magnetization of the free layer, M_s is the saturation magnetization. $\boldsymbol{\sigma}$ is the unit vector of spin polarization direction in y-axis, and $\boldsymbol{m}_p$ is the magnetization of the pinned layer aligned to x-axis. $\boldsymbol{H}_{\rm eff}$ is the effective field, which is critical for determining the equilibrium:

$$\boldsymbol{H}_{\rm eff} = (H_k m_x, 0, -H_d m_z), \tag{2}$$

where $H_k = 4\pi M_s(N_y - N_x)$ represents the in-plane anisotropy field, N_i $(i = x, y, z)$ denotes the demagnetization coefficients. The demagnetization field, H_d, is defined as $4\pi M_s(N_z - N_y)$, specifically focusing on the effect of shape anisotropy. $H_{\rm SOT}$ and $H_{\rm STT}$ correspond to the effective field strengths related to SOT and STT, respectively.

According to the Routh-Hurwitz criterion, we calculate the Jacobian matrix in Appendix A. The STT critical switching current density under a given $H_{\rm SOT}$ is obtained as

$$J_{\rm STT,c} = \frac{2\alpha e t_F M_s}{\hbar P}\left(1 - \frac{{H_{\rm SOT}}^2}{H_d H_k}\right)\left(H_k + \frac{{H_d}^2 - 3{H_{\rm SOT}}^2}{2H_d}\right), \tag{3}$$

where e is the electron charge, t_F is the thickness of free layer, $\hbar$ is the reduced Planck constant and P is the spin polarization efficiency. Eq. (3) is also compatible with the cases of the conventional pure STT and SOT devices. For example, when $H_{\rm SOT} = 0$, it is consistent with the critical switching current density for a pure STT device [1]. When $J_{\rm STT,c} = 0$, the formula could give $H_{\rm SOT} = \sqrt{H_d H_k} \approx \sqrt{4\pi M_s H_k}$

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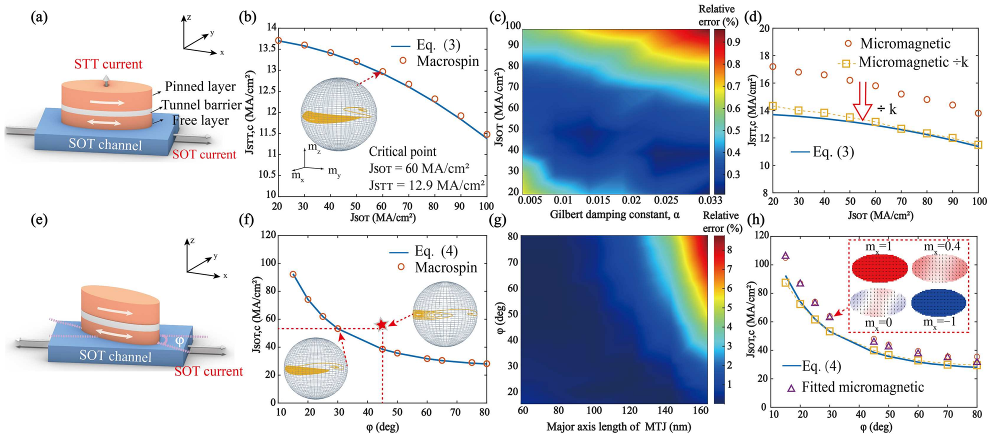

Figure 1 (Color online) Schematics of (a) TST and (e) canted Type-x device. Comparison between theoretical formulas and macrospin simulations of (b) TST device and (f) canted Type-x device, with the insets showing the trajectory of $\boldsymbol{m}$. Relative error analysis of (c) TST device and (g) canted Type-x device. (d) Comparison between (3) and micromagnetic simulations of the TST device, including results modified by a scaling factor k. (h) Comparison between (4) and micromagnetic simulations (red circles) of the canted Type-x device, including the modified curve (yellow squares connected by a dotted line) and fitted results based on pulse-width-dependent switching measurements (purple triangles).

which is identical to the critical condition to activate the instability of the zero-field Type-x device [3].

Furthermore, we extend this approach to the canted Type-x device (see Figure 1(e)), as detailed in Appendix B. The SOT critical switching current density is derived as

$$J_{\mathrm{SOT,c}} = \frac{e t_F M_s}{\hbar\theta_{\mathrm{SHE}}} \frac{2H_d H_k \sin\varphi}{\alpha\,(2H_k + H_d)\cos^2\varphi} \times \left[\sqrt{1 + \frac{\alpha^2 (2H_k + H_d)^2 \cos^2\varphi}{H_d H_k \sin^2\varphi}} - 1\right]. \quad (4)$$

In the cases of $\varphi \to 0$ and $\varphi \to \pi/2$, Eq. (4) is consistent with the formula of the pure Type-x device and the Type-y device [3], respectively. If $\tan\varphi \gg \alpha(2H_k + H_d)/\sqrt{H_d H_k}$, Eq. (4) can be approximately expressed as

$$J_{\mathrm{SOT,c}} \approx \frac{\alpha e t_F M_s\,(2H_k + H_d)}{\hbar\theta_{\mathrm{SHE}} \sin\varphi}, \quad (5)$$

which has a similar form to the switching current density of the canted Type-z device [4]. The relationship of $J_{\mathrm{SOT,c}} \propto 1/\sin\varphi$ has been supported by experimental evidence [5].

Numerical simulation. To validate our theoretical formulas, we conduct both macrospin and micromagnetic simulations. Key parameters are provided in Appendix C.

Figure 1(b) illustrates $J_{\mathrm{STT,c}}$ as a function of J_{SOT} for the TST device. Our theoretical calculations show strong agreement with macrospin simulations. The inset shows the magnetization precessing around the y-axis for an extended period, crossing the yz-plane, and switching to the $-x$ direction. Figure 1(c) presents relative errors of (3), defined as $(J_{\mathrm{STT}} - J_{\mathrm{STT,c}})/J_{\mathrm{STT}} \times 100\%$. The relative errors remain below 0.92% and decrease further as α gets smaller, demonstrating the high accuracy of our formula. Further validation is presented in Figure 1(d), where the theoretical calculations align with the trend of micromagnetic simulations, although slight numerical differences are observed. To minimize this discrepancy, a scaling factor $k = 1.2$ is applied, achieving close alignment between the micromagnetic simulation results and the theoretical formula. This confirms the robustness of the formula for practical implementation.

Further analysis of the canted Type-x device and discussion of Figures 1(f)–(h) are provided in Appendix D.

Conclusion. Based on the Routh-Hurwitz criterion, we have derived theoretical formulas for the critical switching current of two different kinds of field-free Type-x SOT-MTJs. Our approach combines accuracy and simplicity to understand the switching conditions of three-terminal MTJs. The derived formulas align well with numerical simulations, providing valuable insight for scalable design and energy-efficient optimization of SOT-MRAM.

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Supporting information Appendixes A–D. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

References

1 Zhang C, Takeuchi Y, Fukami S, et al. Field-free and sub-ns magnetization switching of magnetic tunnel junctions by combining spin-transfer torque and spin-orbit torque. Appl Phys Lett, 2021, 118: 092406
2 Honjo H, Nguyen T V, Watanabe T, et al. First demonstration of field-free SOT-MRAM with 0.35 ns write speed and 70 thermal stability under 400°C thermal tolerance by canted SOT structure and its advanced patterning/SOT channel technology. In: Proceedings of the IEEE International Electron Devices Meeting (IEDM), 2019
3 Taniguchi T. Switching induced by spin Hall effect in an in-plane magnetized ferromagnet with the easy axis parallel to the current. Phys Rev B, 2020, 102: 104435
4 Lee D K, Lee K J. Spin-orbit torque switching of perpendicular magnetization in ferromagnetic trilayers. Sci Rep, 2020, 10: 1772
5 Liu Y T, Huang Y H, Huang C C, et al. Field-free type-x spin-orbit-torque switching by easy-axis engineering. Phys Rev Appl, 2022, 18: 034019