Threshold current of field-free perpendicular magnetization switching using anomalous spin-orbit torque

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Abstract

Spin-orbit torque (SOT) is a promising technique for next-generation magnetic random-access memory. Recent experiments have shown that materials with low-symmetry crystalline or magnetic structures can generate anomalous SOT with an out-of-plane component, which is crucial for switching the perpendicular magnetization of adjacent ferromagnetic (FM) layers in a field-free condition. In this study, we derive the threshold current for field-free perpendicular magnetization switching using anomalous SOT and numerically calculate the magnetic moment trajectory in an FM free layer for currents smaller and greater than the threshold. We also investigate the dependence of switching time and energy consumption on applied current, finding that the minimum energy consumption decreases with an increasing out-of-plane torque proportion. Additionally, we explore the relationships between the threshold current and anisotropy strength, out-of-plane torque proportion, FM free-layer thickness, and Gilbert damping constant. The results show a negative correlation between the threshold current and out-of-plane torque proportion, and positive correlations with the other three parameters. Finally, we demonstrate that even when the applied current is smaller than the threshold current, it can still add an effective exchange bias field H_{bias} on the FM free layer. The H_{bias} is proportional to the applied current J_{SOT}, facilitating the determination of anomalous SOT efficiency. Our findings provide insights into the design of spintronic devices that favor field-free switching of perpendicular magnetization using anomalous SOT and offer a means of adjusting the exchange bias field to control FM layer magnetization depinning.

Results

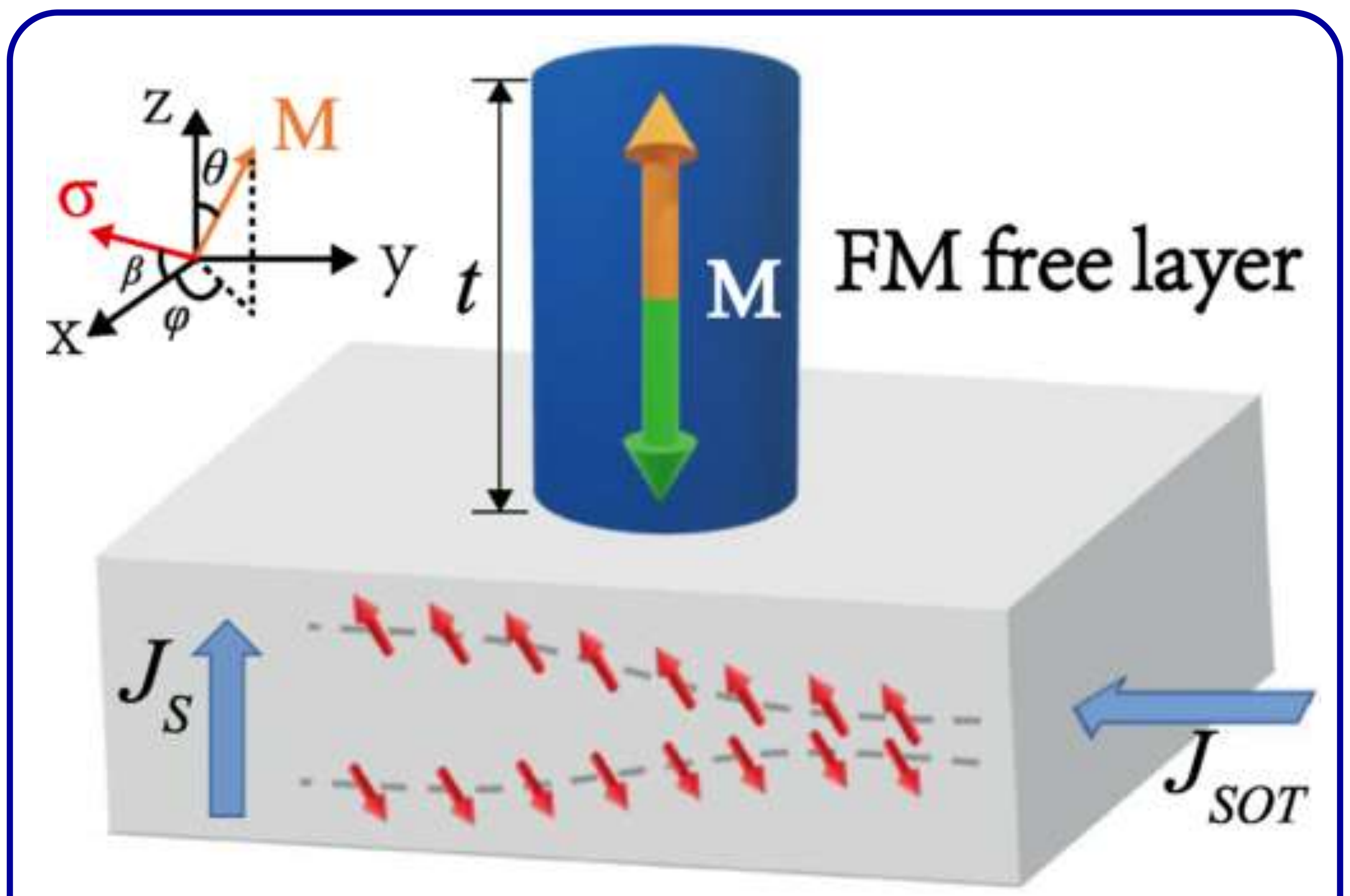

FIG. 1. A schematic diagram of the FM free-layer magnetization switch driven by an anomalous SOT with both in-plane and out-of-plane components. The applied electron current J_{SOT} is along the −y direction and generates a spin current J_s propagating along the z direction. The spin current diffuses into the FM free layer with the perpendicular magnetic anisotropy to drive its magnetization dynamics.

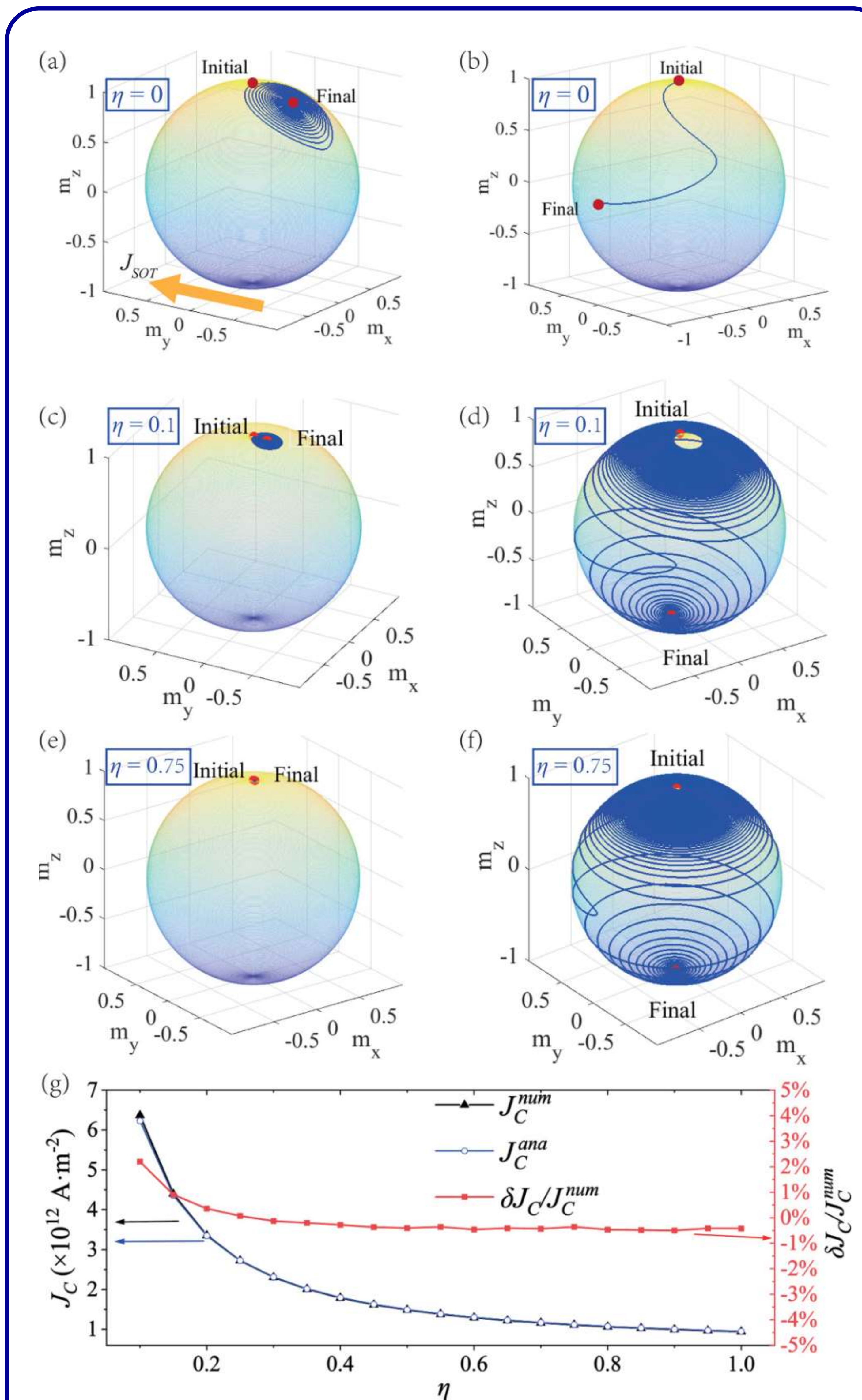

FIG. 2. (a)–(f) The magnetization trajectory with different η and J_{SOT}. The two parameters are shown as follows. η = 0, (a) J_{SOT} = 1.8 × 10^{13} A m^{-2} and (b) J_{SOT} = 1.9 × 10^{13} A m^{-2}; η = 0.1, with threshold current value J_c = 6.23 × 10^{12} A m^{-2}, (c) J_{SOT} = 6.2 × 10^{12} A m^{-2}, and (d) J_{SOT} = 6.37 × 10^{12} A m^{-2}; η = 0.75, with threshold current value J_c = 1.116 × 10^{12} A m^{-2}, (e) J_{SOT} = 1.1 × 10^{12} A m^{-2}, and (f) J_{SOT} = 1.12 × 10^{12} A m^{-2}. (g) The η dependence of analytical threshold current J_C^{ana}, numerical threshold current J_C^{num}, and error $\delta J_C/J_C^{num} = (J_C^{num} - J_C^{ana})/J_C^{num}$.

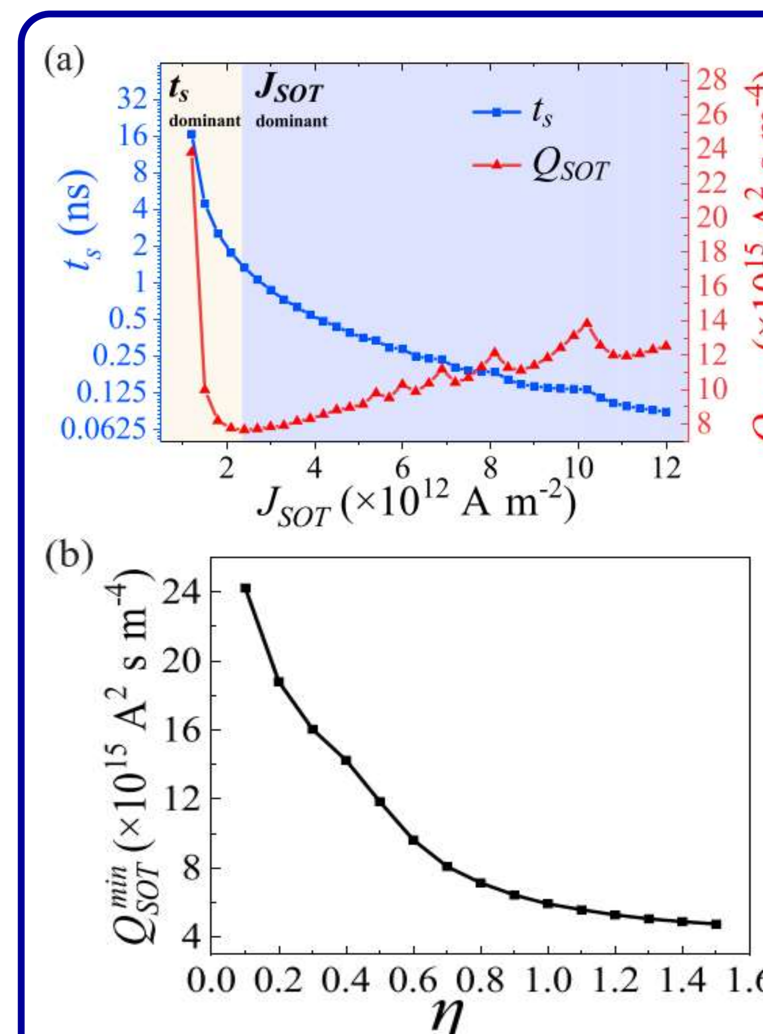

FIG. 3. (a) The J_{SOT} dependence of the switching time t_s and the switching energy consumption Q_{SOT}. (b) The η dependence of minimum energy loss Q_{SOT} min . In the regime of $\eta \le 0.8$, the increase in η can significantly reduce the value of Q_{SOT} min .

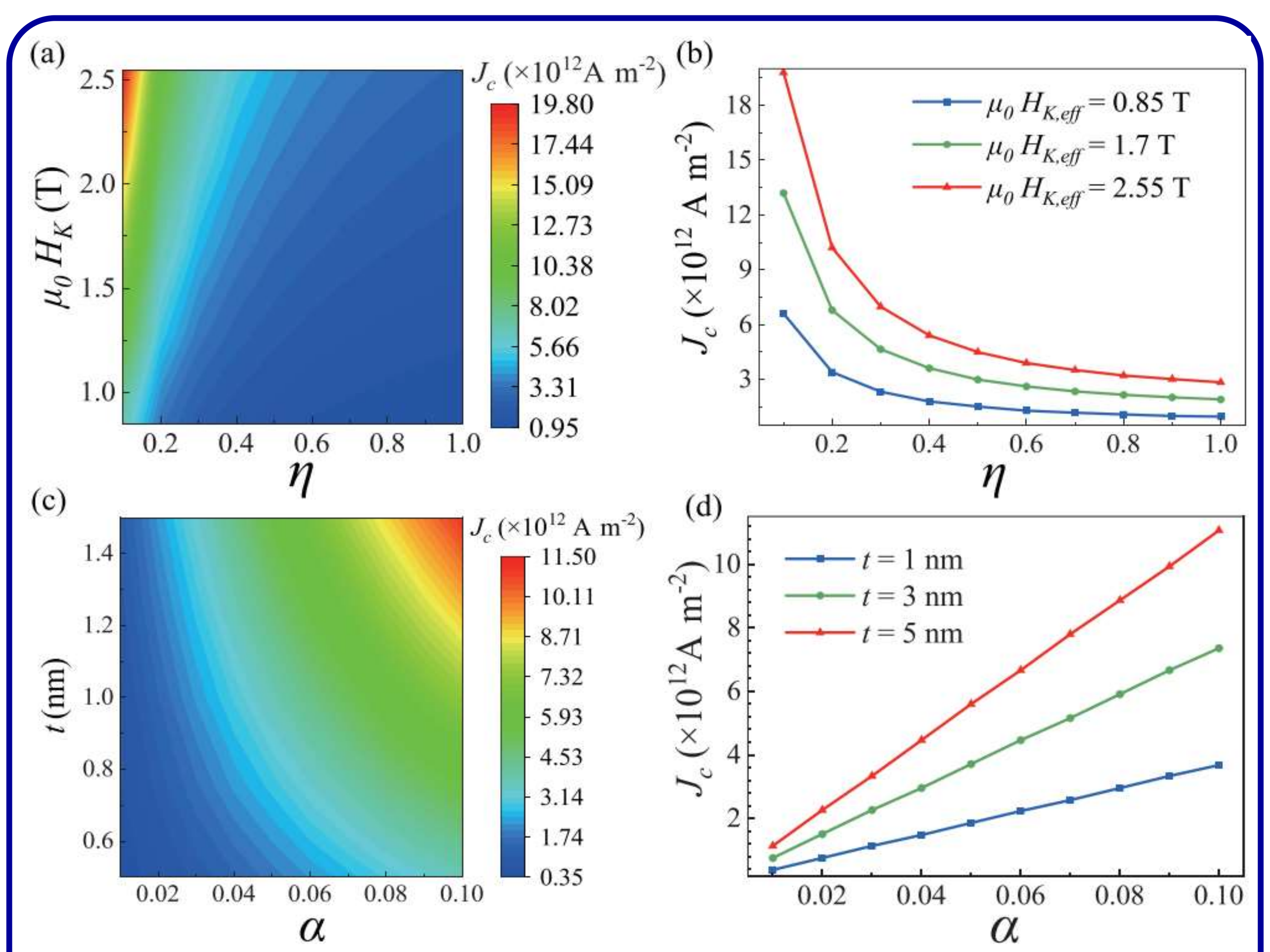

FIG. 4. (a) The dependence of J_c on the anisotropic field H_K and anomalous ratio η. (b) The η dependence of J_c under α = 0.015, t = 1 nm extracted from Fig. 4(a). (c) The dependence of J_c on the thickness t and Gilbert damping α. (d) The η dependence of J_c under $\mu_0 H_K$ = 0.85 T, η = 0.75 extracted from Fig. 4(c).

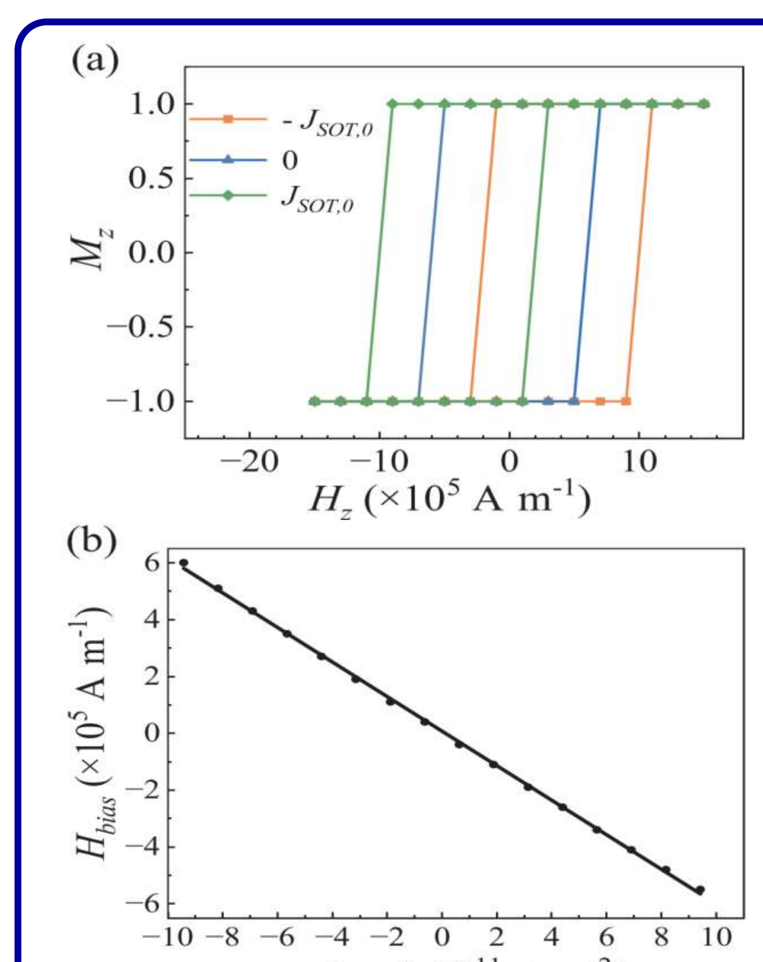

FIG. 5. (a) Hysteresis loop of FM free layer under different applied currents J_{SOT}. (b) Relationship between equivalent exchange bias field H_{bias} and applied current J_{SOT}. Here η = 0.75.

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