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RESEARCH ARTICLE

Field-free switching through bulk spin-orbit torque in $L1_0$-FePt films deposited on vicinal substrates

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Supporting Information

1 SOT switching of the $L1_0$-FePt grown on flat substrates

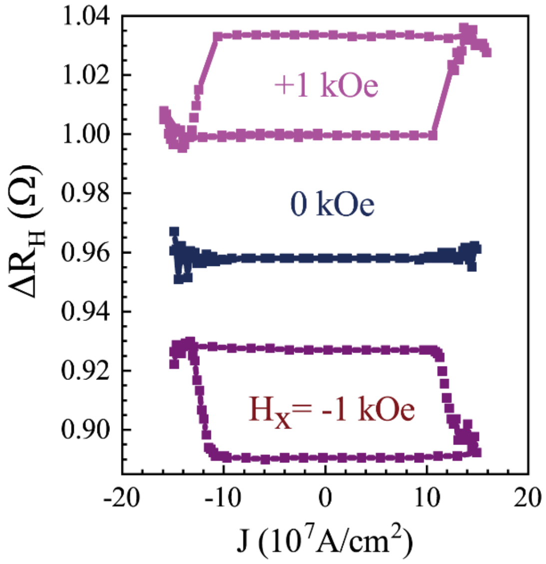

Fig. S1 Current-induced magnetization switching of the 6 nm $L1_0$-FePt grown on flat MgO substrates, with different fields applied along x direction (The R_H at different H_x are offset for clarity.).

2 SOT switching of the $L1_0$-FePt when current is applied in the *y* direction

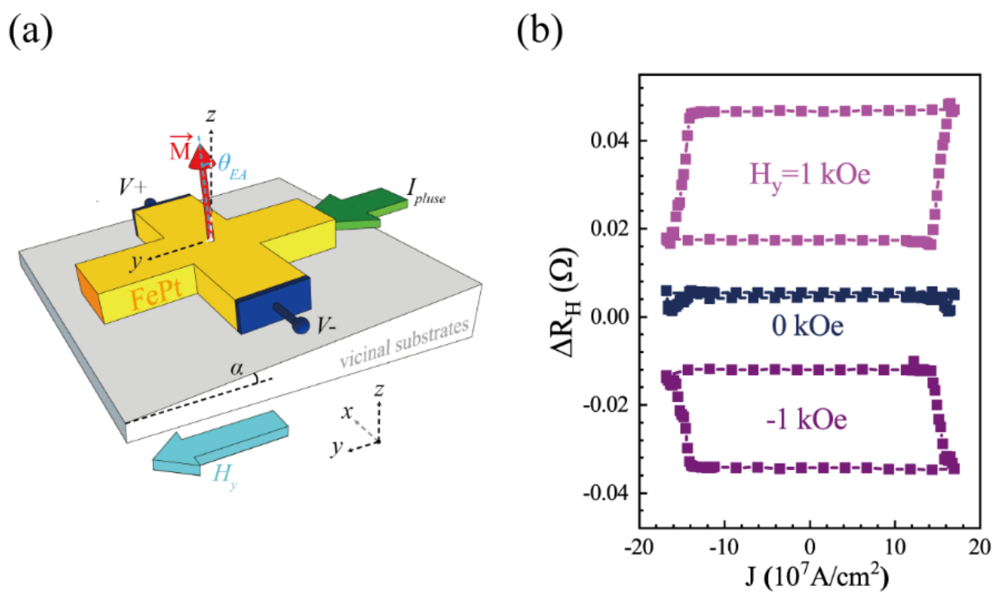

Fig. S2 Current-induced magnetization switching of the 6 nm $L1_0$-FePt grown on vicinal substrate (α=7°), with current applied in the *y* direction. No field-free switching could be realized. The switching could happen when H_y is applied (The R_H at different H_x are offset for clarity.).

3 Field free switching of the $L1_0$-FePt film with different thickness

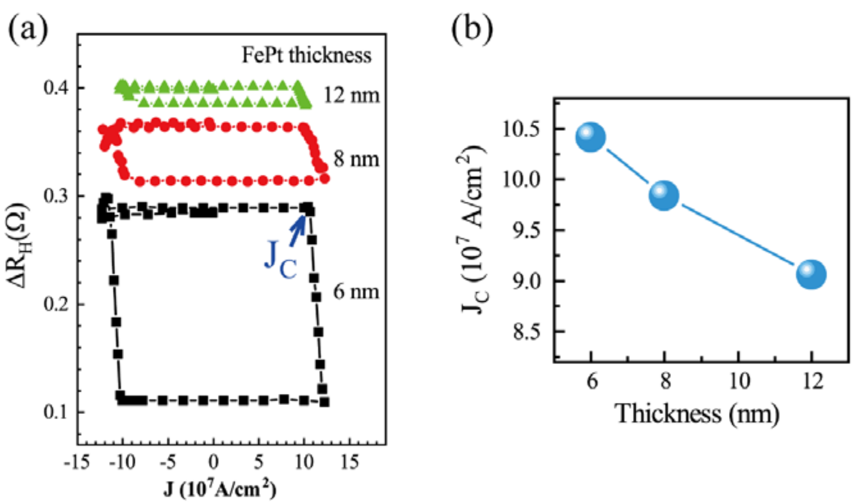

Fig. S3 Current-induced magnetization switching of the $L1_0$-FePt films with different thickness. $L1_0$-FePt grown on vicinal substrate (α=7°). No field is applied. The critical switching current density J_c decrease with the increasing film thickness (The R_H at different H_x are offset for clarity.).

4 Micro-magnetization simulation

We performed micro-magnetization simulation to verify the rotational symmetry of the AMR signals and the field free SOT switching of the FePt magnetization, by using OOMMF. In our simulation model, we choose a FePt film with 200 nm × 50 nm × 6 nm (length × width × thickness) in size, the unit cell size is 5 nm × 5 nm × 6 nm. In our simulation, the magnetic parameters of FePt are as follows: the stiffness of FePt: A=9×10^{-12} J/m; saturation magnetization: M_s=1×10^{6}A/m; the perpendicular anisotropy is K_u=1.5×10^6 J/m^3, damping α=0.01. We compare the simulation results with perpendicular and titled anisotropies, the results are shown in Fig. S4. The simulation shows that film with perpendicular anisotropy could not realize field free switching, see Fig. S4(a). To realize field free switching with tilted anisotropy, the current direction should be perpendicular with the tilting direction of the anisotropy (see Fig. S4(c)), if the current direction is colinear with the tilting direction of the anisotropy, one could not realize field free switching, see Fig. S4(b). Which is consistence with our experiment results. Besides, our simulation shown that when current is colinear with the tilting direction, the switching loop would be asymmetric (shift to -*x* direction,), the shift would decrease with the increasing amplitudes of H_x. In our experiment, we found such asymmetry is small, this may be due to the discrepancy of magnetic parameters between the simulation and the experiments.

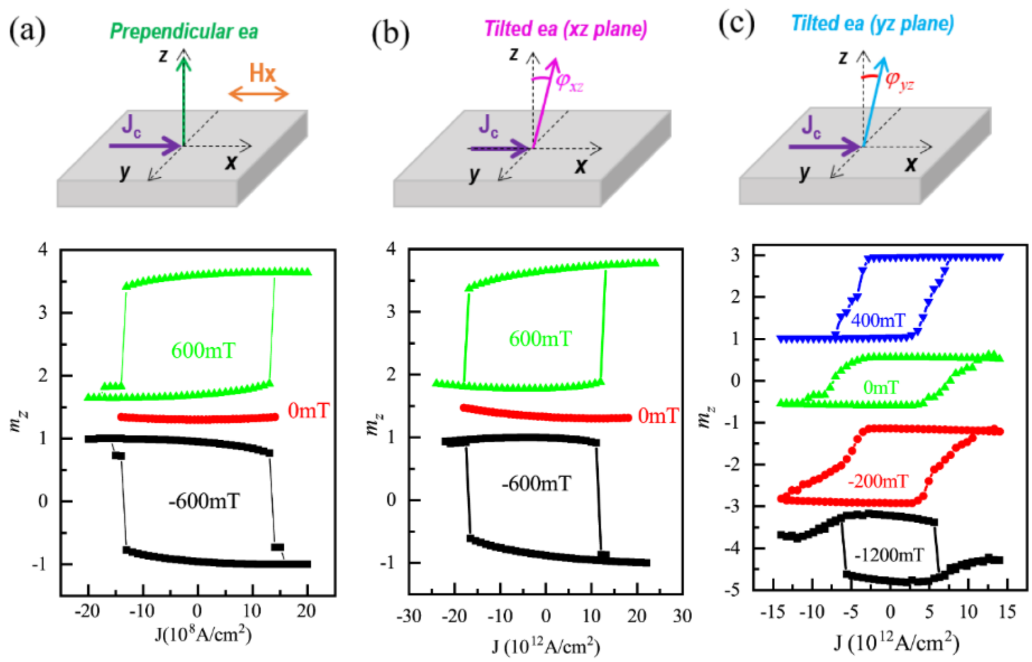

Fig. S4 Simulation of the current induced switching of FePt magnetization, with different anisotropy directions. **(a)** Perpendicular anisotropy. **(b)** Easy axis tilted in the *xz* plane, with tilting angle J_{xz}=8°. **(c)** Easy axis tilted in the *yz* plane, with tilting angle J_{yz}=8°. In each figure, the direction of easy axis, current direction, and field direction are schematically shown in the top panel, and the simulation results are shown in the bottom panel.

5 Spin-orbit torque induced effective fields as a function of the current amplitudes

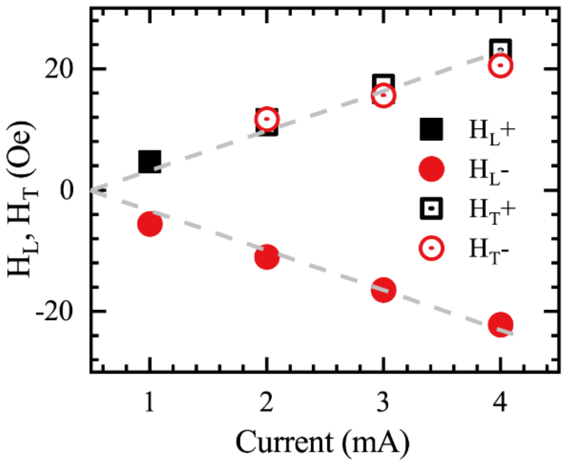

Fig. S5 $H_{L(T)}$ as a function of the current amplitudes. The "+" ("-") represent results obtained from upward (downward) initial FePt magnetization, respectively. The sample we used here is the same as that we used in Figs. 4(c) and (d). The thickness is 6 nm, and the growth temperature is 700°C, the vicinal angle of the substrate is α=7°.

6 VSM measurement result of the FePt film

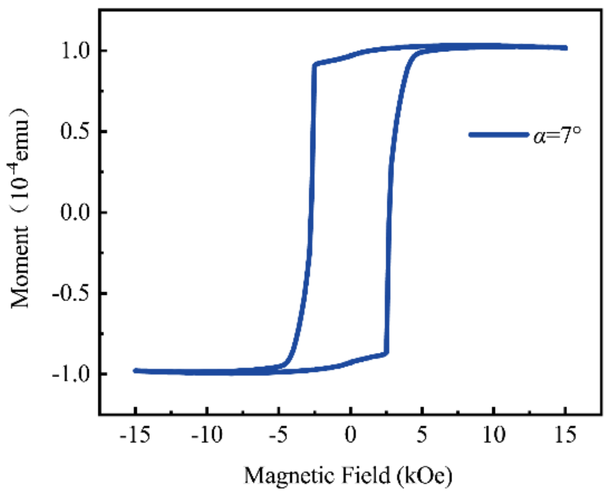

Fig. S6 VSM measurement result of the $L1_0$-FePt film. The thickness of the film is 6 nm, the growth temperature is 700°C, the vicinal angle of the substrate is α = 7°. The sample size is 3 mm×5 mm. The corresponding saturation magnetization is 1.01×106 A/m.

7. Estimation of the anisotropy field of the *$L1_0$*-FePt film.

Fig. S7. (a) Anomalous Hall loops of a 6 nm FePt grown on flat substrates by sweeping field in the direction with $\theta=0°$ and $\theta=90°$. The applied ac current has an amplitude of $I=100\ \mu A$. (b). Normalized M_X versus H (red line) extracted from data of the loop with $\theta=0°$.

We characterize anisotropy of FePt films by measuring anomalous Hall effect (AHE) [I. M. Miron et al., Nat Mater 9, 230 (2010).]. **Fig. S7**(a) shows the AHE loops with θ=0º (hard axis, in-plane) and $\theta=90°$ (easy axis, out of plane) for a 6 nm FePt grown on flat substrate. The two AHE loops have the same magnitude of Hall voltages, confirming that saturated magnetized states were kept during sweeping field. As $V_H \propto M_Z$, the normalized M_Z can be obtained by normalizing the AHE loop. Then the normalized M_X was obtained by the relation of $M_X=\sqrt{1-M_Z^2}$. **Fig. S7**(b) shows the extracted M_X versus H . And the perpendicular anisotropy field H_k is estimated to be the field at which the normalized M_X equals to 0.9 as shown by the blue lines. The H_k is estimated to be 5.3 T. Previous results have shown that the H_K would vary 3.5 to 5.5 T [M. Tang et al., ADV MATER 32, 2002607 (2020).]. This is consistent with previous results.

8. AFM results for flat and vicinal MgO substrate.

Fig S8. AFM results for flat and vicinal MgO substrate. (a) Flat substrate. (b) Vicinal substrates with vicinal angle (α=7°). In (a) and (b), the left is the two-dimensional picture,