SUPPLEMENTARY MATERIAL:
Tailoring the switching efficiency of magnetic tunnel junctions by the fieldlike spin-orbit torque

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1. SOT SWITCHING FOR DIFFERENT PULSE WIDTHS

To confirm that the observed variation of the critical switching voltage in an external field B_{ext} noncollinear with current is independent of the pulse parameters, we measured the critical switching voltage as a function of φ for two different pulse widths. Figure S1 compares $|V_{\text{c}}|$ obtained for switching induced by $t_{\text{p}} = 1$ ns (full squares) and 10 ns (open circles), shown in Fig. 2(c) in the main text. Both datasets follow the same trend, including the opposite slope for both pulse polarities, the location of the crossing point on the left of $\varphi = 0°$, and the relative difference of $|V_{\text{c}}|$ between the reversal supported and hindered by the FLT.

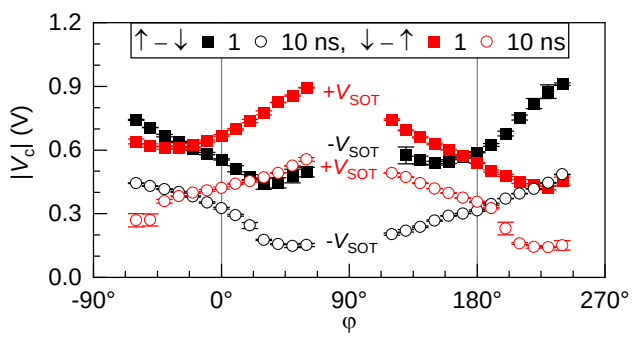

FIG. S1. Dependence of the critical switching voltage V_{c} on the direction of B_{ext} with respect to x for two different pulse widths. The data are obtained at $|B_{\text{ext}}| = 40$ mT using the W-based MTJ.

Moreover, Fig. S1 also shows the switching for the opposite direction of B_{ext}, i.e., for φ close to 180°. In this case, the longitudinal B_x component has the opposite sign with respect to the switching at $\varphi = 0°$. Thus, the switching polarity is reversed and the positive (negative) SOT pulse induces the up-to-down (down-to-up) reversal. The overall trend however remains the same, in agreement with the explanation by the FLT: the y component of the external field subtracts from (adds up to) B_{FL} induced by positive (negative) V_{SOT} for $\varphi \in (0°, 180°)$, whereas the opposite occurs for $\varphi \in (180°, 360°)$. Deterministic switching is not observed for φ close to $\pm 90°$ due to the absence of symmetry-breaking along the x direction.

2. TIME-RESOLVED MEASUREMENTS IN AN MTJ WITH TA UNDERLAYER.

In the main text, we discuss the switching timescales for an MTJ based on W underlayer. In Fig. S2, we show the results measured in a Ta-based MTJ.

Following the same protocol as discussed in the text, we performed single-shot time-resolved switching measurements and extracted the activation delay t_0 and the transition time Δt from individual switching events. Figure S2 summarizes the median values of t_0 and Δt for different field orientations (φ) and the transverse fields strengths (B_y). Notably, the main results are similar in both types of samples. We observe that t_0 is strongly dependent on the external field, and follows the symmetry as observed using the W-based sample, which has the same sign of the SOT. Similarly, Δt remains almost independent of the transverse field, as predicted for Ta [52].

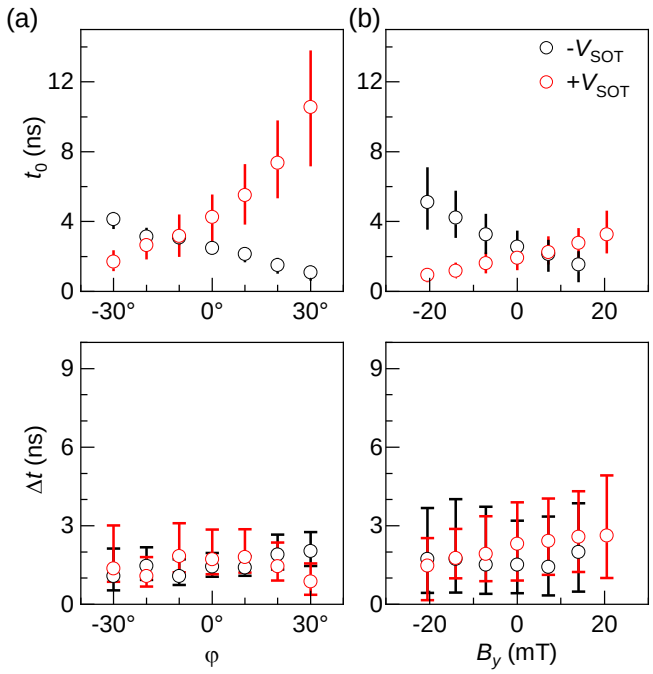

FIG. S2. The activation delay t_0 and the transition time Δt obtained from fitting the switching traces (a) for different φ when $|B_{\mathrm{ext}}| = 40\,\mathrm{mT}$ and (b) for different B_y when $B_x = 40\,\mathrm{mT}$. All measurements are performed in $B_z = 10\,\mathrm{mT}$, which compensates for B_{SAF}. The symbols give the median value obtained from 550 single-shot measurements, the vertical bars give the range of 10–90% of these events.

However, we also observed certain differences with respect to the measurements using the W-based sample. Whereas W allows for reliable switching for both polarities using the same pulse amplitude and a relatively broad range of φ, the switching to the up state is less robust against switching errors when over-critical SOT amplitude is applied in the sample with Ta [see Fig. 1(e) in the main text]. Reliable switching in all trials is important for correct evaluation of the switching times. Therefore, we performed the measurements in a constant external field $B_z = 10\,\mathrm{mT}$, which compensated the SAF field and equalized the difference between the up and down state. This enabled to achieve reliable bipolar switching in a range of transverse fields.

3. SIMULATED MAGNETIZATION TIME TRACES.

We performed a systematic micromagnetic study of the SOT-induced switching as a function of the FLT strength for $|\beta| \leq 1.2$ and the transverse magnetic field given by $|\varphi| \leq 75^\circ$ and $|B_y| \leq 60\,\mathrm{mT}$. Each dynamical simulation allows constructing a time trace that shows the evolution of the z component of the magnetization averaged over the nanomagnet volume, before, during, and after the application of the 1-ns-long SOT pulses. In the simulations, we selected the lowest SOT current that induced the reversal for most combination of the FLT and magnetic field. From each of these time traces, we read the critical switching time t_c as the time from the pulse onset in which the time trace first crossed $m_z = 0$.

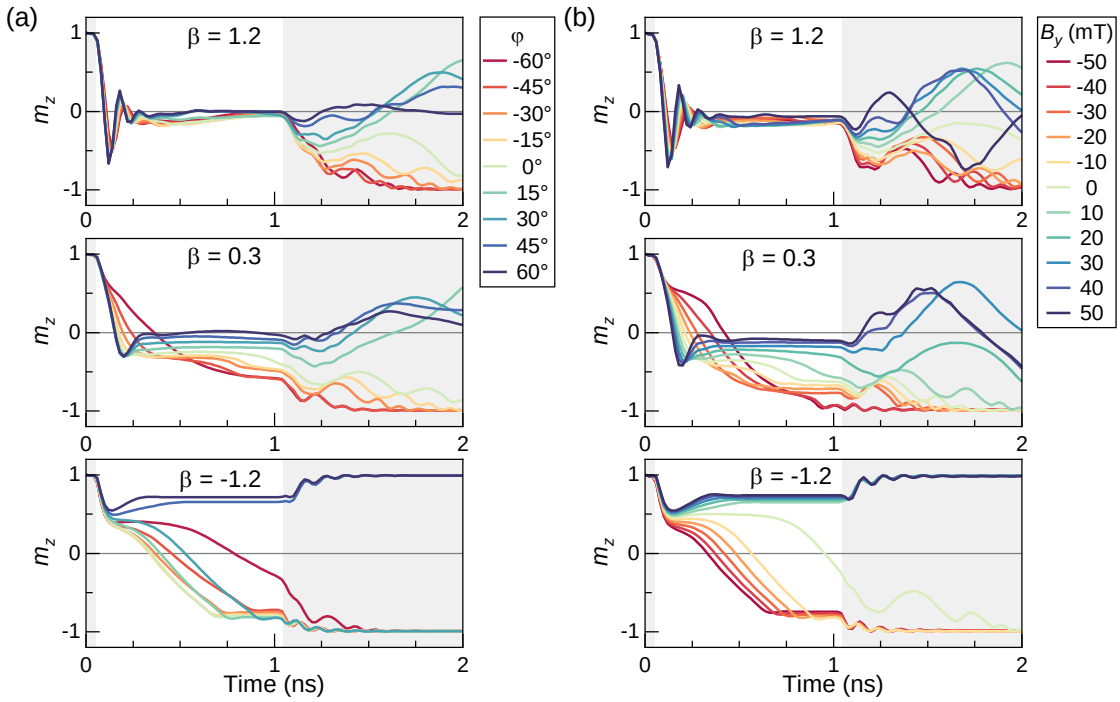

FIG. S3. Simulated time traces of m_z for three different FLT strengths as a function of (a) φ and (b) B_y. The time in which the SOT current is "on" ("off") is indicated by the white (gray) background. In (a) $|B_{\mathrm{ext}}| = 40\,\mathrm{mT}$ and $j_{\mathrm{SOT}} = -130\,\mathrm{MA/cm^2}$, in (b) $B_x = 40\,\mathrm{mT}$ and $j_{\mathrm{SOT}} = -120\,\mathrm{MA/cm^2}$.

Figure S3 shows representative zero-temperature time traces obtained at $j_{\mathrm{SOT}} < 0$ and different fields for large positive β, low positive β as in our W-based samples, and large negative β. The comparison of the three panels shows that the increase of β promotes the switching and reduces t_c.

In these simulations, positive β implies that B_{FL} shortens the reversal time t_c for a positive φ, as it adds to the y component of the external field, in agreement with the measurements reported in Fig. 4 of the main text. A similar behavior is observed for $\beta = 1.2$ (top panel) and $\beta = 0.3$ (middle panel). However, when $\beta = -1.2$ (bottom panel), B_{FL} and the y component of the external field oppose each other at positive φ, which hinders the reversal. In this configuration, the highest φ values correspond to the under-critical conditions, at which the reversal does not initiate.

Beside the effect on t_c, positive B_{FL} promotes the magnetization precession. This is revealed in the time traces by the damped oscillations of m_z at the beginning of the current pulse before the equilibrium state with the spin polarization is reached.

After the SOT pulse, the micromagnetic state relaxes to the energy minimum. For large φ, however, $B_x = B_{\mathrm{ext}}\cos(\varphi)$ can become too low to efficiently drive a domain wall in the absence of the SOT current, which results in an intermediate state for a prolonged time after the pulse end for positive β [top panel in Fig. S3(a)]. Only after a finite time that depends on the damping parameter, the magnetization relaxes to the up or down state. It is, however, less likely to complete the reversal to the final (down) state than in the case of low or negative β. Experimentally, this would be interpreted as an increased susceptibility to switching errors, as it was observed in Ta-based samples [26, 30], and attributed to a B_{FL}-induced reflection of the propagating

domain wall from the side of the magnetic layer.

Note that replacing B_{FL} by a transverse magnetic field along the same direction leads to an equivalent outcome. For positive β, this can be observed in Fig. S3 for $\varphi > 0$ or $B_y > 0$. On the other hand, a transverse magnetic field opposing B_{FL} ($\varphi < 0$ or $B_y < 0$) hinders the reversal, which results in longer t_{c}, but also increases reliability of the switching to the final state. This corresponds well to the experimental results presented in Fig. 2 in the main text, where we found that the reliability of the switching to the down state decreases with increasing $\varphi > 0$.

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