Nanosecond-Timescale Low Energy Switching of In-Plane Magnetic Tunnel Junctions through Dynamic Oersted-Field-Assisted Spin Hall Effect

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Supporting Information

ABSTRACT: We investigate fast-pulse switching of in-plane-magnetized magnetic tunnel junctions (MTJs) within 3-terminal devices in which spin-transfer torque is applied to the MTJ by the giant spin Hall effect. We measure reliable switching, with write error rates down to $10^{-5}$, using current pulses as short as just 2 ns in duration. This represents the fastest reliable switching reported to date for any spin-torque-driven magnetic memory geometry and corresponds to a characteristic time scale that is significantly shorter than predicted possible within a macrospin model for in-plane MTJs subject to thermal fluctuations at room temperature. Using micromagnetic simulations, we show that in the three-terminal spin-Hall devices the Oersted magnetic field generated by the pulse current strongly modifies the magnetic dynamics excited by the spin-Hall torque, enabling this unanticipated performance improvement. Our results suggest that in-plane MTJs controlled by Oersted-field-assisted spin-Hall torque are a promising candidate for both cache memory applications requiring high speed and for cryogenic memories requiring low write energies.

KEYWORDS: Spintronics, spin Hall effect, magnetic tunnel junction, magnetic memory, spin orbit torque, MRAM

Magnetic random access memory (MRAM) controlled using spin transfer torque (STT),1−3 using either in-plane4−6 or perpendicularly magnetized7,8 magnetic tunnel junctions (MTJs), holds promise for replacing existing best-in-class memory technologies in several application domains because it offers the potential for nonvolatility, unlimited read and write endurance, low write energy, and low standby power. For the wide application of STT-MRAM technology it is also crucial to achieve high-speed switching with low write error rates (WERs). Currently, the fastest reliable ($<10^{-5}$ WER) switching times reported for conventional two-terminal STT-MRAM are 35 ns for in-plane MTJs6 and 4 ns for perpendicular MTJs.8 Theoretical and experimental analyses have led to skepticism about the possibility for significant improvements in switching speed and reliability, particularly for in-plane magnetized devices.4,9 Consequently, the search for speed has led to more ambitious proposals including orthogonal spin-transfer (OST) MRAM,10 where subnanosecond switching has been demonstrated but via a precessional nondeterministic time scale that is significantly shorter than predicted possible within a macrospin model for in-plane MTJs subject to thermal fluctuations at room temperature. Here, we investigate the speed and reliability of spin-orbit torque11−15 switching in three-terminal devices16−20 that utilize the spin Hall effect (SHE)21,22 to achieve efficient switching of an in-plane magnetized MTJ. We demonstrate reliable ($\leq 10^{-5}$ WER) switching using current pulses only 2 ns long. This is faster than the best reported value for reliable switching of any previous spin-torque MRAM device,4,9−9 in-plane or perpendicularly magnetized, with a characteristic time scale even faster than the theoretical limit expected for in-plane-magnetized MTJs in the macrospin approximation.5,2,4

Figure 1a shows a schematic representation of our three-terminal device geometry (SEM micrograph in Figure 1b). We use a 5 nm thick Pt spin-Hall channel to generate a spin current that impinges on a Fe$_{60}$Co$_{20}$B$_{20}$ nanomagnet free layer that is part of a magnetic tunnel junction. The reference layer of the MTJ is a FeCoB/Ru/FeCoB synthetic antiferromagnetic (the full wafer stack and fabrication technique are described in the Supporting Information). A 0.7 nm Hf spacer between the Pt and FeCoB free layer is used in order to reduce the magnetic damping, following Nguyen et al.18 We report data from three devices with different aspect ratios for the MTJ: a low aspect ratio (“LA”, dimension 190 × 110 nm$^2$, aspect ratio 1:1.7, coercivity, $H_c$, 14 Oe), medium (“MA”, 190 × 75 nm$^2$, 1:2.5, 30 Oe) and high (“HA”, 190 × 45 nm$^2$, 1:4.2, 54 Oe). In the free layer of these MTJs, the aspect ratio determines the in-plane anisotropy and therefore the thermal stability factor, $\Delta$, which is the ratio of the energy barrier ($E_b$) for switching normalized by the thermal energy ($k_B T$). The MTJs are patterned by electron-beam lithography as rounded rectangular features on top of a 335 nm wide Pt/Hf channel with a channel resistance for all
devices of 1.05 kΩ. The resistance-area product of the MTJ barrier is \( \sim 190 \, \Omega \cdot \mu m^2 \) (see Supporting Information for measurement details). All the measurements we report were performed at room temperature.

Figure 1c shows magnetic-field-driven hysteresis curves for the devices with different aspect ratios. There is a residual dipole field \( (H_{\text{eff}} = 2S, 62, 65 \, \text{Oe} \) for LA, MA, and HA devices) due to slight imperfection in balancing the synthetic antiferromagnetic layer that causes the centers of the hysteresis curves to be shifted from zero; the data in Figure 1c are plotted relative to this offset. The parallel-state (P) MTJ resistances are 13.1, 14.3, and 21.7 kΩ, whereas the antiparallel (AP) state resistances are 19.9, 29.3, and 45.6 kΩ for the LA, MA, and HA devices, respectively. Consequently the tunneling magnetoresistance (TMR) is \( \sim 110\% \) for MA and HA devices with a lower value (52%) for the LA device. The P state resistance of the LA device is higher than expected based on the resistance-area product of the MA and HA devices (Figure 1d, also see Figure S1 in Supporting Information). We therefore ascribe the reduced TMR of the LA device to a greater degree of spatial nonuniformity in its magnetic state, so that the P state resistance in the LA device is not fully saturated due to a weaker shape anisotropy.

In order to obtain quantitative measurements of the spin Hall effect in these devices, we first conduct direct current (dc) switching experiments (Figure 2a). These are performed using an external offset field bias \( (H_{\text{ext}} = -H_{\text{off}}) \) to center the hysteresis loops (as in Figure 1c). The dependence of the critical switching current density on the ramping rate of the current density \( (J) \) allows us to obtain the critical switching current density\(^2\) in the absence of thermal fluctuations \( (J_{c0}) \) and the thermal stability factor \( (\Delta = E_b/k_B T) \) at room temperature:

\[
\langle J \rangle = J_{c0} \left( 1 + \frac{1}{\Delta} \ln \left( \frac{J}{J_{c0}} \right) \right)
\]

where \( \tau_0 \) is the thermal fluctuation time, taken to be 1 ns. Table 1 summarizes the dc switching characteristics measured for the three devices.

To explore the device performance in the fast switching regime, we perform measurements of switching probability as a function of pulse voltage and pulse duration (see Supporting Information for illustrative examples of the results of such measurements). Interpolating from these measurements, we can extract the pulse durations that result in 50% switching probability for each pulse voltage used. Figure 2 shows the data and fit to these values using the macrospin model relation\(^2\)

\[
V(\tau) = V_{c0} \left( 1 + \frac{t_0}{\tau} \right)
\]

where \( V_{c0} \) is the critical pulse switching voltage and \( t_0 \) is the critical pulse switching duration, both defined at the 50% switching probability point. \( t_0 \) represents the time scale needed

Figure 1. (a) Schematic of the device with directions of charge current \( J_e \) and spin current \( J_s \) as well as the spin accumulation \( \sigma \). The Oersted field wraps around the Pt channel and opposes the anisotropy field in the nanomagnet during switching. (b) SEM micrograph of a representative MTJ and the spin-Hall channel obtained before top leads deposition. (c) Easy axis hysteresis loops show differences in coercive field corresponding to the aspect ratio of the MTJs.

Figure 2. (a) The dc switching current densities measured with a range of current ramp-rates for the three devices. (b–d) Pulsed voltage amplitudes required to achieve 50% probability of switching for a given pulse length. Lines in panel a are fits to eq 1 and in panels b–d are fits to eq 2.
Table 1. Critical dc and Pulsed Switching Parameters of the Three-Terminal Devices

<table>
<thead>
<tr>
<th></th>
<th>LA</th>
<th>MA</th>
<th>HA</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>device</strong></td>
<td>3.1 ± 0.3</td>
<td>4.4 ± 0.3</td>
<td>4.0 ± 0.3</td>
</tr>
<tr>
<td><strong>Δ</strong></td>
<td>36 ± 2</td>
<td>44 ± 3</td>
<td>54 ± 5</td>
</tr>
<tr>
<td><strong>Hc [kA/m]</strong></td>
<td>1.11</td>
<td>2.44</td>
<td>4.30</td>
</tr>
<tr>
<td><strong>Vc (AP→P) [V]</strong></td>
<td>0.58 ± 0.05</td>
<td>0.62 ± 0.05</td>
<td>0.61 ± 0.05</td>
</tr>
<tr>
<td><strong>tc (AP→P) [ns]</strong></td>
<td>0.43 ± 0.07</td>
<td>0.65 ± 0.09</td>
<td>1.00 ± 0.15</td>
</tr>
<tr>
<td><strong>Vc (P→AP) [V]</strong></td>
<td>0.59 ± 0.02</td>
<td>0.61 ± 0.04</td>
<td>0.59 ± 0.02</td>
</tr>
<tr>
<td><strong>tc (P→AP) [ns]</strong></td>
<td>0.18 ± 0.02</td>
<td>0.56 ± 0.06</td>
<td>1.18 ± 0.07</td>
</tr>
</tbody>
</table>

“The dc switching parameters are averaged between AP-to-P and P-to-AP polarities, as these quantities are within experimental error. The pulse switching experiments reveal nontrivial asymmetries in AP-to-P and P-to-AP switching dynamics.”

Figure 3. In the absence of an Oersted field, the switching mechanism for both AP-to-P (a→b→d) and P-to-AP (d→f→a) are dominated by a highly nonuniform micromagnetic intermediate states. In contrast, switching in the presence of the Oersted field proceeds through near-uniform intermediate states. The time required to complete the switching process is also significantly shorter in the presence of the Oersted field, for both AP-to-P (a→c→d) and P-to-AP (d→e→a) polarities. The intermediate states are representative snapshots taken near the halfway time (t/2) of the respective switching simulation.

for a sample biased at Vc to absorb the amount of angular momentum required for fast switching, assuming no loss to damping.

The voltage scales for switching, Vc, are the same for the three aspect ratios within experimental error (Table 1). This validates our understanding that the energetics of the switching are determined by the strength of the spin Hall effect and the geometry of the Pt channel in the pulse switching regime, both of which are the same for all three devices in this report. On the other hand, the dynamics of the switching shows surprising results, which vary in detail with the aspect ratio. First, in all cases the results indicate a remarkably fast time scale, t ≤ ∼1 ns, considerably less than the ns time scale expected from the antidamping switching mechanism for an in-plane magnetized free layer in the rigid domain approximation. In addition, the values obtained for t show a clear dependence on the device aspect ratio with the low aspect ratio device having the fastest observed switching speed. Finally, there appears to be a growing asymmetry between the P-to-AP and AP-to-P polarity switching speeds as the aspect ratio is reduced.

To understand the origin of this unexpected but technologically important speed-up in the switching speeds, we perform zero-temperature micromagnetic simulations of a representative device to capture the behavior during switching (see movies of simulations in Supporting Information). Our simulations indicate that the Oersted field generated by the current flowing in the Pt/Hf channel plays a key role in assisting the switching process that is driven by the spin Hall torque. It is important to note that the Oersted field in our three-terminal spin Hall devices is oriented differently than in conventional two-terminal STT-MRAM, where the field is circularly symmetric about the device since the current flows through the MTJ itself. In the three-terminal geometry, the Oersted field is approximately uniform and in-plane. The strength of the Oersted field (∼1 kA/m at a current density of 4 × 10^11 A/m^2 in the Pt/Hf channel) can become comparable and is opposite in direction to the anisotropy field of the free layer (given the sign of the spin Hall effect in Pt). Still, it is surprising that the Oersted field should have a large effect on the switching within a macrospin picture because for antidamping spin-torque switching the strength of the anisotropy field should have minimal impact on the critical current. The switching trajectory of the magnetization, at least within the context of a macrospin, rigid-domain approximation should also remain largely unaffected by the magnitude of the anisotropy field. Nevertheless, in the micromagnetic simulations we observe a striking difference in the switching mechanism depending on whether the Oersted field is turned on or off. In Figure 3, the a→b→d sequence...
shows micromagnetic snapshots of the AP-to-P switching process for a simulation with no Oersted field; highly nonuniform micromagnetic states are generated during the switching process. This is qualitatively similar to the excitation of short-wavelength spin wave modes observed in simulations of some conventional STT devices. However, this nonuniformity is in marked contrast to the AP-to-P simulation with the Oersted field (a→c→d in Figure 3), where the switching process progresses through significantly more uniform states. A similar distinction is also observed in the P-to-AP switching without (d→f→a) and with (d→e→a) the Oersted field. Quantitatively, the simulations indicate that the switching is completed faster with the Oersted field, especially in the P-to-AP polarity in this particular simulation. In addition, the switching is seen to start immediately upon the application of current (t = 0 in the simulations), which suggests the lack of any extended buildup of precessional amplitude, or incubation time, especially because the simulations are performed at 0 K temperature. We note that the incubation time has remained a major technological limitation factor for high-speed switching of in-plane STT-MRAM devices. On the basis of these observations from the micromagnetic simulations, we conclude that the fast switching is enabled by the combination of the following three factors: (1) the micromagnetic curvature of the free-layer magnetization that ensures a nonzero initial torque; (2) the suppression of higher order spin-wave modes in the magnetization by the Oersted field that would otherwise hinder the completion of the reversal; and (3) the avoidance of macrospin-type stagnation points due to the nonuniformities in the micromagnetic states during the switching process.

While the limited-statistics pulse voltage and duration sweeps such as shown in Figure 2 and the Supporting Information are routinely used to report the existence of high-speed switching, a much more rigorous test of switching reliability is required to demonstrate feasibility for technological applications. We have tested the reliability of our three-terminal spin Hall devices by measuring WER statistics during up to 10⁵ switching attempts for each pulse duration and pulse voltage of interest. Figure 4a,b shows the measured WERs with 5 and 2 ns pulse durations, respectively, for the three devices. Three key results are immediately apparent from these plots. First, the WERs for 5 ns pulse durations demonstrate single-exponential scaling down to WERs of 10⁻⁵ for all three devices, indicating that the micromagnetic switching trajectories are highly reliable and scale very favorably with the applied pulse voltage. Second, the WER scaling trend highlights a significant interplay between the Oersted field and the anisotropy field scale, whereas all three devices exhibit fast reliable switching: the lower the coercive field, the greater the effect of the Oersted field in reliably speeding the reversal. Finally, the data demonstrate that the WER with a 2 ns pulse can be driven below 10⁻⁵, most clearly in the MA device. We do observe multieponential features at low WERs, especially for the HA and LA devices, for either P-to-AP and AP-to-P polarities, reminiscent of the “low probability bifurcated switching” and back-hopping mechanisms discussed by Min et al. However, we emphasize that the WER data presented here are for a pulse duration of 2 ns, which is an order of magnitude shorter than the 50 ns pulse durations that were explored by Min et al. Quantitatively, this 2 ns time scale precludes many of the explanations for the multiexponential behavior based on macrospin-type switching mechanisms. We therefore conclude that this behavior in our devices stems instead from the rich micromagnetic switching mechanism at these previously unexplored speeds. Specifically, the multiexponential features are likely due to a particular device’s atomic-scale edge roughness, pinning, and any local nonuniformities of the free layer and can therefore can be further optimized for improved performance in the 2 ns regime.

We will refer to this previously unexplored and technologically attractive reversal mechanism as “dynamic Oersted-field-assisted spin Hall effect” (DOFA-SHE) switching. On the basis of the insight from the micromagnetic simulations, we conclude that the fast and reliable switching that we measure is a general consequence of the in-plane Oersted field orientation present in the three-terminal geometry. As discussed above, although there is clearly a correlation of the degree of enhancement of the reversal speed with the coercivity of the device, the effect cannot simply be attributed to the Oersted field overcoming the coercive field. This conclusion gains further support from the fact that we have also performed fast pulse switching experiments with a HA MTJ on a Ta spin-Hall channel that has a larger but negative spin-Hall angle (~ −0.15 vs +0.08 for our Pt devices), This change in sign results in the Oersted field pointing along the anisotropy field during switching. Despite this change in direction we find that the Ta device also has subnanosecond t₀ for both AP-to-P and P-to-AP switching with a similar scaling of the WER as the Pt HA device (see Supporting Information). We emphasize that the Oersted field

Figure 4. WERs for (a) 5 ns pulses and (b) 2 ns pulses. Both panels show WERs for the three devices with different aspect ratios as a function of normalized pulsed voltage. Open triangles represent data points where the measured error was zero. Dashed lines connecting the data points are provided as a visual guide. Solid lines are single-exponential fits that allow for estimation of the voltages needed to achieve error rates of 10⁻⁵.
does not have any detrimental effect on the long time scale thermal stability of the devices because the field is only present during the pulse that drives switching. We anticipate that the Oersted field can be engineered to optimally assist the switching of nanomagnets of a desired thermal stability by optimizing the spin-Hall channel’s geometry, resistivity, spin-Hall torque efficiency and spin diffusion length.

In summary, we have established DOFA-SHE-switched in-plane-magnetized three-terminal MTJs as an attractive architecture to achieve highly reliable magnetic switching for pulse times down to 2 ns or potentially shorter. This mechanism does not require an external magnetic field to make the switching deterministic, one of the difficulties facing the development of perpendicularly magnetized MTJs switched using spin–orbit torques. The 3-terminal DOFA-SHE geometry also has additional advantages over conventional 2-terminal STT-MRAM to minimize read times as well as to reduce read disturbeds (because large currents do not flow through the MTJ itself). The beneficial speed-up of switching due to the Oersted field in the three-terminal geometry not only allows the SHE switching of in-plane MTJs to be faster than demonstrated for any other magnetic memory geometry, but it also opens up new avenues for optimizing device performance in terms of data retention versus write speed. In particular, our results suggest that the nonvolatile nature of magnetic memories can now be fully harnessed for both long-term data retention applications (requiring large $\Delta$), as well as for fast switching applications (requiring small $t_{\text{on}}$) where data retention is not a primary concern. Finally, DOFA-SHE might prove attractive for cryogenic memory applications where the thermal stability of small (~1) aspect ratio MTJs is increased due to the low temperatures, thereby enhancing the relative role of the Oersted field from the spin-Hall channel.

ASSOCIATED CONTENT

Supporting Information
The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.nanolett.6b01443.

Fabrication, measurement and simulation details; magnetic property characterization; pulse switching probability measurements. (PDF)
Simulated micromagnetic pulse switching trajectories, AP to P, without Oersted field. (AVI)
Simulated micromagnetic pulse switching trajectories, AP to P, with Oersted field. (AVI)
Simulated micromagnetic pulse switching trajectories, AP to AP, without Oersted field. (AVI)
Simulated micromagnetic pulse switching trajectories, P to AP, without Oersted field. (AVI)
Simulated micromagnetic pulse switching trajectories, P to AP, with Oersted field. (AVI)

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Author Contributions
S.V.A. fabricated the devices, the experiments with the guidance of R.A.B. and D.C.R. G.E.R. performed the micromagnetic simulations and constructed the pulse switching instrumentation. J.O. performed the electrical measurements with the help of S.V.A and G.E.R. S.V.A. wrote the manuscript with feedback from all authors. S.V.A and G.E.R. contributed equally to this work.

Notes
The authors declare no competing financial interest.

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