Reduced Current Spin-Orbit Torque Switching of a Perpendicularly Magnetized Free Layer

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Abstract— **We demonstrate the switching of a perpendicularly magnetized free layer by spin-orbit torques with reduced currents. The switching is accomplished by a purely electrical, two-current pulse scheme. The reduced current can be applied to many cells in an array, but only flipping the one that is pre-selected with the spin-orbit torque of the first pulse. A robust switching is observed for a current as low as 50% of the critical one, which also reduces the power consumption of the writing operation.**

Keywords - Spin-orbit torque MRAM, perpendicular magnetization, magnetic field free switching, two-pulse switching scheme

Spin-orbit torque (SOT) magnetoresistive random access memory (MRAM) is a viable candidate for a non-volatile replacement of high-level caches, as it delivers high operation speed and large endurance. However, for a deterministic SOT switching of a perpendicularly magnetized free layer (FL) an external magnetic field is required. Several field-free schemes have been proposed [1]-[6], however a large-scale integration and/or scaling of such schemes can be difficult. An alternative, recently proposed field-free scheme is based on a purely electrical switching controlled by two orthogonal current pulses. This scheme is viable for switching of an in-plane and a perpendicularly magnetized free-layer (FL). Furthermore, it is rather robust [7]. Nevertheless, the large currents needed to realize the switching are still an issue.

In this work, based on extensive micromagnetic simulations, we demonstrate that after a pre-selection of the cell by a first current pulse, the switching current of the second pulse can be reduced by about 50% and still guarantee a deterministic and fast switching of a perpendicularly magnetized FL.

The memory cell and the switching scheme are shown in Fig. 1. The writing SOT-cell is formed by a perpendicularly magnetized FL on top of a heavy metal wire (NM1) and a second, orthogonal heavy metal wire (NM2), which contacts the FL partially. An MTJ is placed next to the SOT-cell for the reading operation. The parameters of the cell are listed in Table I. The stability factor of the cell is about 45. The first current pulse is applied to the NM1 wire, which selects the cell to be written. Then, the second pulse completes the writing.

The applied current density is usually larger than the critical current density

$$J_C = \frac{e}{\hbar}\frac{M_S d}{\theta_{SH}} H_K , \qquad (1)$$

where e is the elementary charge, $\hbar$ is the reduced Plank constant, M_S is the saturation magnetization, d is the FL thickness, θ_{SH} is an effective Hall angle, and H_K is the effective anisotropy field. The first pulse has a current I_1 = 130 μA and a fixed duration of T_1 = 130 ps. This yields a current density j_1=2.1x10^{12} A/m^2, which is just above the critical one. This current puts the magnetization in the plane of the FL perpendicularly to the current direction. Then, the second current pulse is applied through the NM2 wire completing the switching. The magnetization dynamics of the magnetic system is described by the Landau-Lifshitz-Gilbert equation

$$\frac{\partial \mathbf{m}}{\partial t} = -\gamma\mu_0 \mathbf{m}\times\mathbf{H}_{\mathrm{eff}} + \alpha\mathbf{m}\times\frac{\partial \mathbf{m}}{\partial t} - \gamma\frac{\hbar}{2e}\frac{\theta_{SH} j}{M_S d}\left[\mathbf{m}\times\left(\mathbf{m}\times(\mathbf{j}\times\mathbf{z})\right)\right], \qquad (2)$$

where $\mathbf{m}$ is the normalized magnetization, γ is the gyromagnetic ratio, μ_0 is the vacuum permeability, α is the Gilbert damping, j is the current density, and $\mathbf{H}_{\mathrm{eff}}$ includes the exchange field, uniaxial perpendicular anisotropy field, demagnetization field, current-induced field, and random thermal field at 300K.

Fig. 2 shows the switching dynamics for I_2 = 130 μA (j_2 = 2.1x10^{12} A/m^2) for various pulse durations T_2. The switching is deterministic and robust, with switching times about 0.3 ns (taken at m_z = -0.5) for $T_2 \geq$ 100 ps. Considering that many cells are typically connected as an array in a memory circuit, the application of a current near the critical one increases the probability of undesired switching of non-selected cells. Therefore, it is important to reduce the switching current. Fig. 3 shows the magnetization switching for several current magnitudes below the critical one. Surprisingly, even for a current reduction as large as 50%, the switching characteristics are still preserved, i.e., the switching remains deterministic, robust, and fast. It was observed that the switching becomes non-deterministic for a current below 50% of the critical one. Since the second pulse current is significantly weaker, just the pre-selected cell is flipped, while the probability of switching non-selected cells in a row is much smaller.

Fig. 4 shows the switching times as a function of the second current magnitude and duration. For $T_2 \geq 150$ ps, I_2 can be reduced to 50% of the critical value for the same switching performance. Moreover, the reduced current has also the important advantage of lower power consumption for the writing process.

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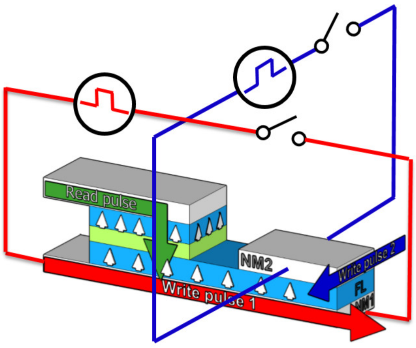

Figure 1. Two-pulse switching for an SOT-cell with a perpendicularly magnetized FL.

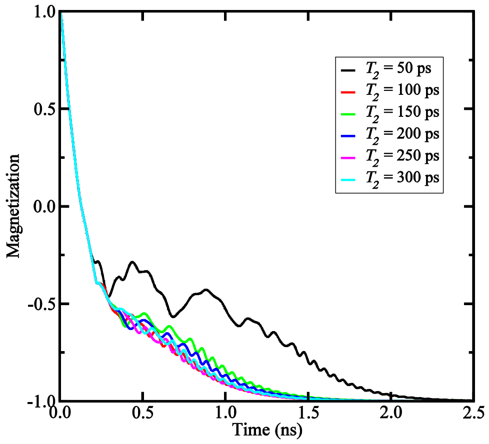

Figure 2. Average of 20 switching realizations for several second pulse durations, T_2. The simulation parameters are: $I_{1,2}$ = 130 µA, T_1 = 130 ps.

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TABLE I. PARAMETERS USED IN THE SIMULATIONS. HEAVY METAL WIRES ASSUMED OF TUNGSTEN, WHILE THE MAGNETIC FL IS OF COFEB ON MGO [2].

Saturation magnetization, M_S	1.1×10^6 A/m
Exchange constant, A	1.0×10^{-11} J/m
Perpendicular anisotropy, K	8.4×10^5 J/m^3
Gilbert damping, α	0.035
Spin Hall angle, Θ_{SH}	0.3
Free layer dimensions	40 × 20 × 1.2 nm^3
NM1: $w_1\times l$	20 × 3 nm^2
NM2: $w_2\times l$	20 × 3 nm^2

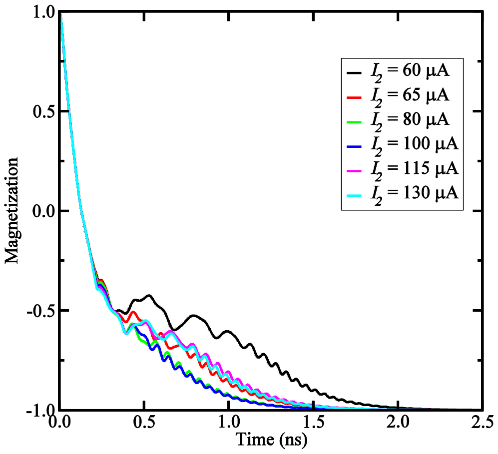

Figure 3. Switching realizations for different current values for the second pulse. Simulation parameters: I_1 = 130 µA, T_1 = 130 ps, T_2 = 150 ps.

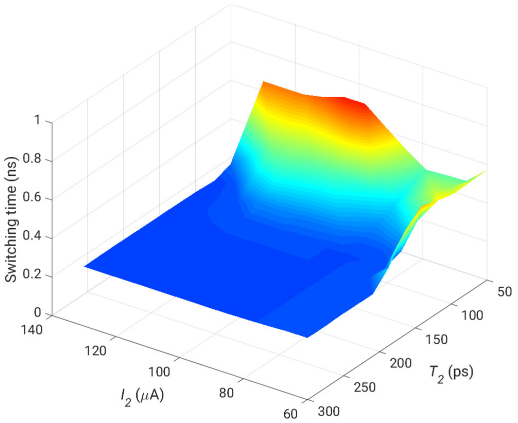

Figure 4. Switching time as function of I_2 and T_2.