Robust Magnetic Field Free Switching Scheme for Perpendicular Free Layer in Advanced Spin Orbit Torque Magnetoresistive Random Access Memory

R. Orio[1], A. Makarov[2], S. Selberherr[2], W. Gös[3],
J. Ender[1], S. Fiorentini[1], V. Sverdlov[1]
[1]Christian Doppler Laboratory for Nonvolatile Magnetoresistive Memory and Logic at the
[2]Institute for Microelectronics, TU Wien, Austria
[3]Silvaco Europe Ltd., Cambridge, United Kingdom
{orio|sverdlov}@iue.tuwien.ac.at

The continuous increase in performance and speed of modern integrated circuits is steadily supported by miniaturization of the complementary metal-oxide semiconductor (CMOS) devices. However, a rapid increase of dynamic and stand-by power due to transistor leakages becomes a pressing issue. A promising way to overcome this issue is to introduce non-volatility in circuits. The development of an electrically addressable non-volatile memory combining high speed and high endurance is essential to achieve this goal. To reduce the energy consumption in particularly CPUs, one can replace the SRAM in hierarchical multi-level processor memory structures with a non-volatile memory [1]. Spin-orbit torque magnetoresistive random access memory (SOT-MRAM) combines non-volatility, high speed, and high endurance and is thus perfectly suited for applications in caches. However, its development is still hindered by the need of an external magnetic field for deterministic switching of perpendicularly magnetized layers [2].

We demonstrate that the fast (sub-500ps), deterministic, and magnetic field free switching of a perpendicularly magnetized rectangular recording layer achieved by employing two orthogonal short (100ps) current pulses of duration T_1 and T_2 running through the two heavy metal lines NM1 and NM2 of thickness l and widths w_1 and w_2 in a cross-bar array shown in Fig.1 is extremely robust with respect to the pulse synchronization failure. It yields a large confidence window for the time delay τ (positive or negative) between the two pulses.

Similar to the set-up suggested earlier [3], the NM2 line has an incomplete overlap with the free layer (Fig.1). The magnetization dynamics is described by the Landau-Lifshitz-Gilbert equation supplemented with the SOTs generated by the currents $I_{1,2}$ and acting on the free magnetic layer of the thickness $d = 2$nm:

$$\begin{aligned}\frac{\partial \mathbf{m}}{\partial t} = -\gamma \mathbf{m} \times \mathbf{H}_{\mathrm{eff}} + \alpha \mathbf{m} \times \frac{\partial \mathbf{m}}{\partial t} + \gamma \frac{\hbar}{2e} \frac{\Theta_{SH} I_1}{M_S d w_1 l} [\mathbf{m} \times (\mathbf{m} \times \mathbf{y})] \Theta(t) \Theta(T_1 - t) \\ - \gamma \frac{\hbar}{2e} \frac{\Theta_{SH} I_2}{M_S d w_2 t} [\mathbf{m} \times (\mathbf{m} \times \mathbf{x})] \Theta(t - T_1 - \tau) \Theta(T_2 + T_1 + \tau \\ - t), \qquad (1)\end{aligned}$$

where $\mathbf{m}$ is the position-dependent magnetization $\mathbf{M}$ normalized by the saturation magnetization M_S, γ is the gyromagnetic ratio, α is the Gilbert damping, e is the elementary charge, $\hbar$ is the reduced Plank constant, and Θ_{SH} is an effective Hall angle. $\mathbf{H}_{\mathrm{eff}}$ includes the exchange, anisotropy (see Table 1), demagnetization, and random thermal field at 300K.

The duration of the “Write pulse 1” of 100µA is fixed to $T_1 = 100$ps. T_2, τ, and I_2 of “Write pulse 2” vary. When NM2 has a full overlap w_2 of 52.5nm with the free layer, the switching by the two consecutive 100µA pulses is robust *only*, if the second pulse is either short (50-70ps) or long (>1ns) (Fig.2). The switching becomes fully deterministic for a broad range of the “Write pulse 2” duration T_2 if either the current through NM2 is increased to I_2=200µA (Fig.3) or the overlap of NM2 with the free layer is reduced to ~1/3 (Fig.1), for the same I_2=100µA current (Fig.4). The “Write pulse 1” puts the magnetization of the free layer in-plane perpendicular to the “Write pulse 1” direction (Fig.2, Fig.3). Depending on the “Write pulse 2” polarity, the corresponding SOT slightly tilts the magnetization in-plane towards the left or right end of the rectangle. Then the magnetization experiences the shape anisotropy field, which plays the role of the external field to complete the switching 100% reliably. Fig.5 shows that the switching is extremely robust with respect to the delay τ, which proves the scheme suitable for practical implementation.

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[2] S. Fukami, T. Anekawa, C. Zhan, and H. Ohno, Nature Nanotechnology **11**, 621 (2016).

[3] V. Sverdlov, A. Makarov, and S. Selberherr, J.Systemics, Cybernetics and Informatics **16**, 55 (2018).

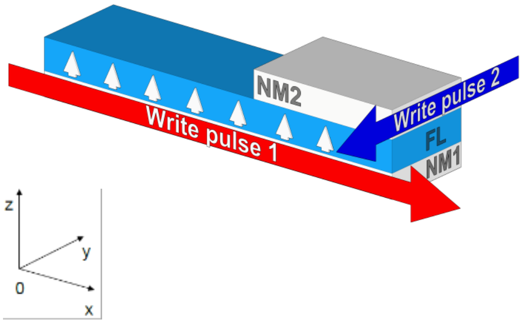

Fig.1 Schematic structure of the two-pulse switching scheme applied to the perpendicularly polarized magnetic free layer (FL).

Name	**Value**
Saturation magnetization M_S	4×10^5 A/m
Exchange constant A	2×10^{-11} J/m
Perpendicular anisotropy K	2×10^5 J/m^3
Gilbert damping α	0.05
Spin Hall angle Θ_{SH}	0.3
Free layer dimensions	52.5×12.5×2nm^3
NM1: $w_1\times l$	12.5nm×3nm
NM2: $w_2\times l$	5-52.5nm×3nm

Table 1 Parameter values used in the simulations. They correspond to CoFeB FL on tungsten (NM1 and NM2).

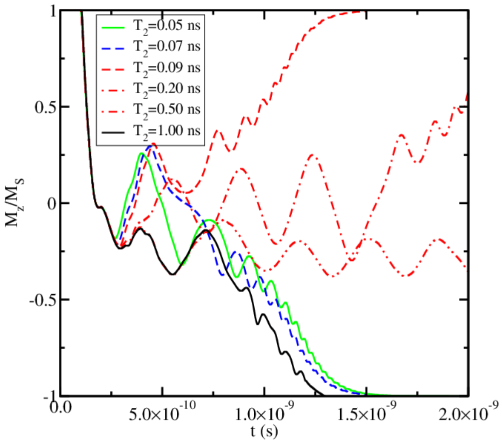

Fig.2 $m_z(t)$ for NM2 fully overlapping with FL averaged for 20 realizations. $I_1=I_2=100\mu A$. For $70ps<T_2<1ns$ the switching fails (shown in red).

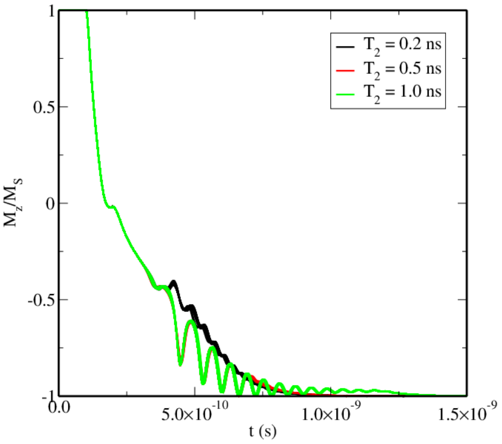

Fig.3 20 realizations of magnetization switching for NM2 fully overlapping with FL (w_2=52.5nm) similarly to Fig.1, but with I_2 increased to 200μA.

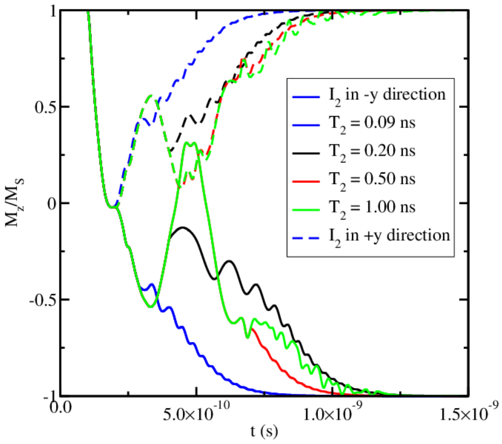

Fig.4 Average of 20 realizations of $m_z(t)$, with $m_z(0)=1$ for NM2=12.5nm, $I_1= I_2=100\mu A$, several T_2, and $\tau=0$. I_2 along –y reliably switches m_z while I_2 of the opposite polarity brings it to the initial state.

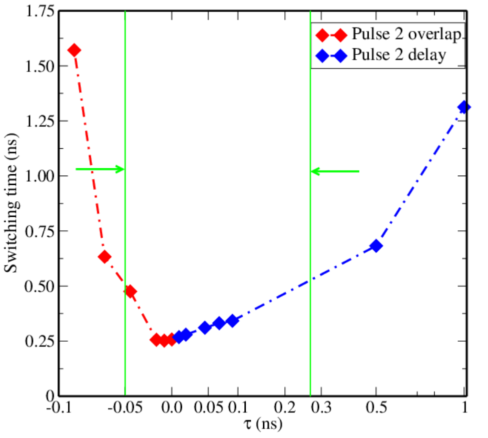

Fig.5 Robust switching at pulse delays between -90ps<τ<1ns (defined in (1)), for $w_1=w_2$=12.5nm and equal Write pulses 1,2 ($I_1=I_2=100\mu A$, $T_1=T_2$=100ps). Sub 0.5ns switching is obtained at -50ps<τ<250ps.

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