Efficient Magnetic Field Free Switching of Symmetric Perpendicular Magnetic Free Layer for Advanced SOT-MRAM

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Abstract— **A long-standing problem of magnetic field free switching of a symmetric perpendicular free layer by spin-orbit torque is resolved by employing two perpendicular consecutive current pulses. The optimal overlap of the second pulse line is found to be around 50%. Robustness of switching with respect to small fluctuations of the second current pulse duration and of the overlap with the free layer are demonstrated.**

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

Spin-transfer torque magnetic RAM (STT-MRAM) is fast, possesses high endurance (10^{12}), and has a simple structure. It is compatible with CMOS and can be straightforwardly embedded in circuits. It is particularly promising for use in IoT and automotive applications, a replacement of conventional flash memory as well as for embedded applications [1]. However, the switching current of STT-MRAM is fairly high, and devices based on a new principle are required. The spin-orbit torque (SOT) assisted switching of a free layer (FL) is promising as the current is passing through a heavy normal metal (NM) wire on which the FL is grown [1]. However, a static magnetic field is still required for deterministic switching [2] of the FL. Even though several paths to achieve a field-free switching were reported, they require a local intrusion into the cell fabrication, which makes large scale integration problematic.

In this work we demonstrate that a magnetic field free two-pulse switching scheme [3] previously proposed to switch a perpendicular FL of rectangular form is suitable to switch a symmetric square FL. In contrast to the in-plane anisotropy field employed for deterministic switching of a rectangular FL, an in-plane stray magnetic field of a part of the square FL under the NM2 wire (Fig.1) acting on the rest of the FL is used to deterministically switch the symmetric FL. We also demonstrate that the switching scheme is robust with respect to the variations of the duration T_2 of the second pulse and fluctuations of the NM2 wire's partial overlap w_2 with the FL.

TABLE I. PARAMETERS USED IN THE SIMULATIONS

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	25×25×2nm^3
NM1: $w_1\times l$	25 nm×3nm
NM2: $w_2\times l$	5-25nm×3nm

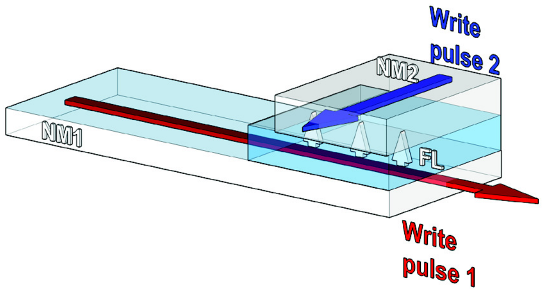

Figure 1. Two-pulse switching scheme applied to the perpendicularly polarized square magnetic free layer (FL).

The memory cell is shown in Fig.1. It includes a perpendicularly magnetized FL on top of a heavy metal wire (NM1). The parameters of FL are listed in Table 1. To guarantee a minimal thermal stability factor of 40 making the cell suitable for SRAM applications we chose the FL dimensions $a\times a\times d$=25×25×2nm^3. FL overlaps fully with NM1 of l=3nm thickness. The first pulse of a fixed duration $T_1 = 200$ps and fixed current I_1=100μA is applied through NM1. Another heavy metal wire (NM2) of l=3nm overlaps partly with FL, $w_2 < a$, serves to apply the second consecutive perpendicular current pulse $I_2=(w_2/a)200$μA of the same current density as in "Write pulse 1", with a variable duration T_2. The magnetization dynamics of the magnetic system is described by the Landau-Lifshitz-Gilbert equation:

$$\frac{\partial \mathbf{m}}{\partial t} = -\gamma \mathbf{m}\times\mathbf{H}_{\mathrm{eff}} + \boldsymbol{\alpha}\mathbf{m}\times\frac{\partial \mathbf{m}}{\partial t} +$$

$$\gamma\frac{\hbar}{2e}\frac{\Theta_{SH}I_1}{M_S d w_1 l}[\mathbf{m}\times(\mathbf{m}\times\mathbf{y})]\Theta(t)\Theta(T_1-\mathrm{t}) -$$

$$\gamma\frac{\hbar}{2e}\frac{\Theta_{SH}I_2}{M_S d w_2 l}[\mathbf{m}\times(\mathbf{m}\times\mathbf{x})]\Theta(t-T_1)\Theta(T_2+T_1-\mathrm{t}) \quad (1)$$

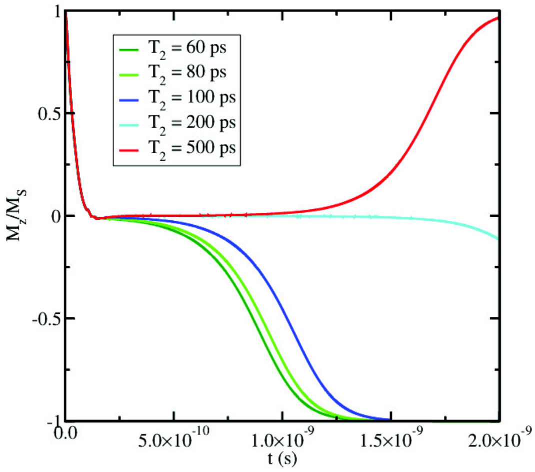

Figure 2. Average of 20 switching realizations. For partial overlap w_2 =17.5nm, reliable switching fof square FL at short T_2 “Write current 2”pulses duration appears.

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

In the case of full overlap of NM2 with FL, no “Write pulse 2” parameters were detected which would support deterministic switching of FL. This is in contrast to the SOT-MRAM cell with a rectangular layer, where the shape anisotropy played the role of the external magnetic field, while the switching direction was determined by the polarity of the “Write pulse 2”, which pushed the magnetization to one or another side from the in-plane direction along the short side of the rectangle. As there is no uniaxial shape anisotropy for a square FL, the switching is unreliable for the full overlap w_2=25nm.

Surprisingly, when the NM2 overlap with FL is reduced to w_2=17.5nm, deterministic switching is observed for all 20 realizations, if the duration T_2 of “Write pulse 2” becomes shorter than 200ps (Fig.2). If now the overlap w_2 is further reduced below 15nm, the switching becomes deterministic for all pulse durations T_2 considered. Fig.3 demonstrates the average over 20 realizations for time dependencies of magnetization switching, for w_2=10nm and several T_2 . For 60ps<T_2<100ps the curves nearly coincide.

The inset in Fig.3 demonstrates the position dependent magnetization just after the “Write pulse 2” was turned on. The magnetization under NM2 gets rotated due to the SOT of the second pulse. The stray field of the magnetization under NM2 creates an effective in-plane magnetic field for the rest of FL. This field makes the magnetization to precess away from its in-plane orientation. The whole magnetization of FL precesses in the same sense, if “Write pulse 2” is short, which is the reason of the switching scheme’s robustness

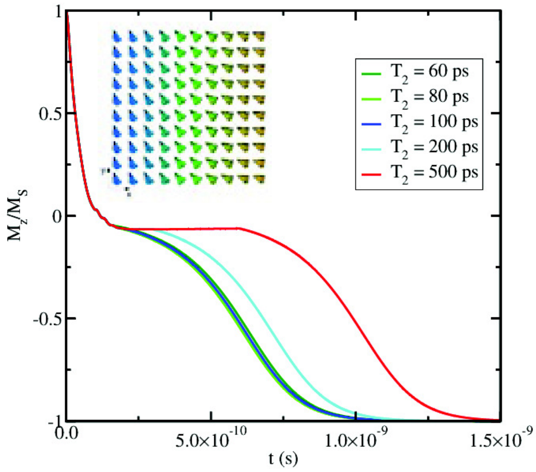

Figure 3. Average of 20 switching realizations for w_2=10nm. Reliable switching is observed for all T_2. Inset: snapshot of magnetization just after “Write pulse 2” is on.

with respect to T_2 fluctuations around T_2 =80ps. Fig.4 proves the main result of the work that the switching scheme is robust not only with respect to T_2=80±20ps fluctuation, but also to fluctuations of w_2=11±4nm as almost the same switching time is observed.

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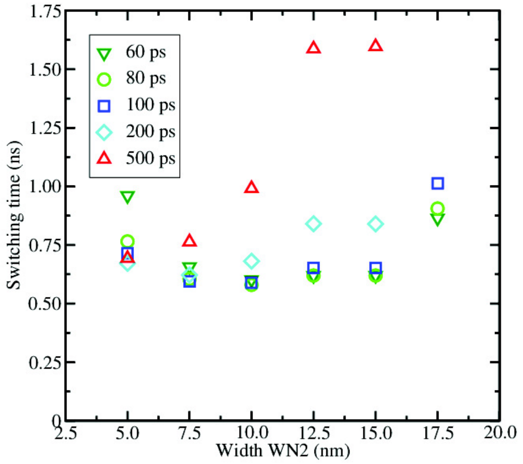

Figure 4. Switching time as function of w_2 for several T_2.