SOT-MRAM based on 1Transistor-1MTJ-Cell Structure

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***Abstract*—We propose a new method of soft magnetic layer switching based on torques generated by the spin Hall effect and show a possibility of building 1Transistor-1MTJ cells with different paths for read and write operations. By performing extensive micromagnetic modeling our switching method has been verified.**

Keywords - MTJ; MRAM; spin Hall effect; cross-point architecture

I. INTRODUCTION

Magnetic tunnel junction (MTJ) based spin transfer torque magnetoresistive random-access memory (STT-MRAM) is one of the promising candidates for future universal memory. It combines non-volatility, fast access and potentially small size [1, 2]. The conventional MTJ-based memory designs assume two-terminal devices with reading based on the tunnel magnetoresistance and writing based on the (spin-torque due to the) spin-polarized current passing through the MTJ. The two main shortcomings of the two-terminal devices are reliability and endurance: indeed, (i) the high write current density can occasionally damage the MTJ barrier and (ii) it remains a challenge to guarantee reliable reading without ever causing switching [2]. These shortcomings do not exist in the three-terminal memory cells [3, 4]. In these devices different paths are used for read and write operations and as a consequence the high write current does not flow through the MTJ barrier.

Recently, three-terminal devices with spin-orbit torque (SOT) switching were proposed [5, 6]. An SOT memory cell is an MTJ fabricated on a heavy metal channel with large spin-orbit interaction, wherein the free layer is in direct contact with the heavy metal channel. Spin torque is induced by the in-plane current through the spin-orbit coupling effect in terms of the Rashba effect and/or the spin Hall effect (SHE) [7-11]. However, one particular shortcoming is that an external magnetic field is required to provide deterministic switching [12]. The second shortcoming of this memory type compared to the two-terminal devices is that it demands more space and thus leads to a lower area density because of the second transistor required for writing [2, 4].

The second issue can be resolved by a pre-selection of an individual cell by means of a voltage pulse applied to the cell simultaneously with powering the spin Hall metal line. The voltage pulse softens the magnetic anisotropy of the cell's free layer, thus facilitating the magnetization switching of the pre-selected cell [13, 14]. However, this scheme still requires an external magnetic field.

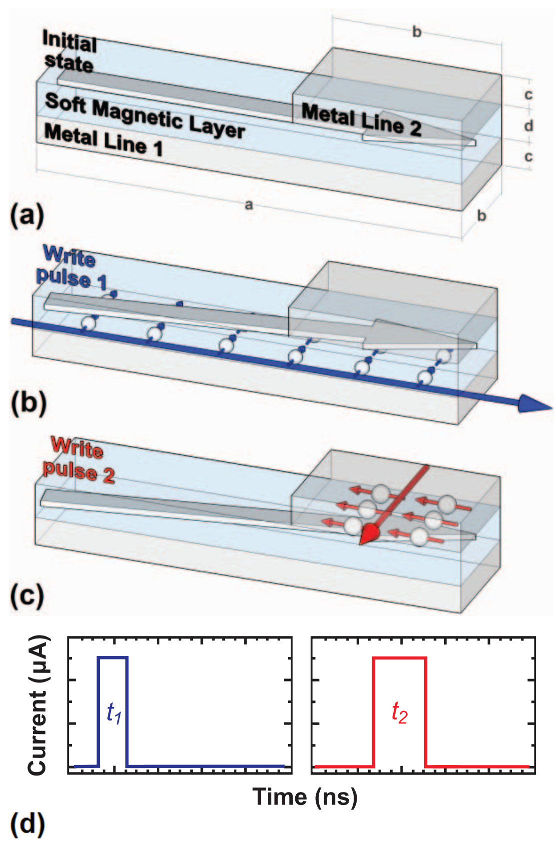

Figure 1. Schematic illustration of the proposed method of soft magnetic layer switching. In (b), (c) The direction of the charge current is shown by big arrows, the direction of the spin current is given by small arrows.

In this work we propose an external magnetic field free method for soft magnetic layer switching based on two consecutive orthogonal sub-nanosecond current pulses. We investigate the proposed method by means of extensive micromagnetic simulations and discuss the possibility of building 1Transistor-1MTJ memory cells in a cross-point architecture.

This research is supported by the European Research Council through the grant #247056 MOSILSPIN.

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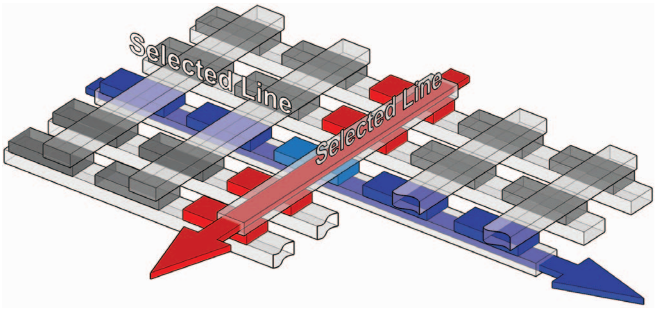

Figure 2. Schematic illustration of cross-point architecture for the switching of the soft magnetic layer by means consecutive orthogonal sub-nanosecond current pulses.

II. Method Description

Figure 1 shows the investigated structures for which the switching operation is based on two consecutive orthogonal sub-nanosecond in-plane current pulses. The switching is governed by the torques generated by the SHE. The first pulse is necessary for tilting the magnetization of the soft layer from its stable state and creating a small initial angle. The second pulse is used for switching the soft layer to a new state.

III. Model Description

Our analyses are based on the magnetization dynamics described by the Landau-Lifschitz-Gilbert (LLG) equation, including the additional SHE term in the areas of current flow [15]

$$\frac{d\mathbf{m}}{dt}=-\frac{\gamma}{1+\alpha^2}\cdot\left(\left(\mathbf{m}\times\mathbf{h}_{\mathbf{eff}}\right)+\alpha\cdot\left[\mathbf{m}\times\left(\mathbf{m}\times\mathbf{h}_{\mathbf{eff}}\right)\right]-\frac{\mu_B j\theta_{SHE}}{e\gamma M_s d}\cdot\left[\mathbf{m}\times\left(\mathbf{m}\times\mathbf{p}\right)\right]\right), \tag{1}$$

and the LLG equation otherwise

$$\frac{d\mathbf{m}}{dt}=-\frac{\gamma}{1+\alpha^2}\cdot\left(\left(\mathbf{m}\times\mathbf{h}_{\mathbf{eff}}\right)+\alpha\cdot\left[\mathbf{m}\times\left(\mathbf{m}\times\mathbf{h}_{\mathbf{eff}}\right)\right]\right). \tag{2}$$

Here, γ=2.3245·10^{5}m/(A·s) is the gyromagnetic ratio, α is the Gilbert damping parameter, μ_B is Bohr's magneton, j is the charge current density, e is the electron charge, θ_{SHE} is the spin Hall angle, d is the thickness of the free layer, $\mathbf{m}=\mathbf{M}/M_s$ is the position dependent normalized vector of the magnetization in the free layer, M_s is the saturation magnetizations of the free layer, and $\mathbf{p}$ is the polarization of the spin current due to the spin-dependent scattering in the metal layer calculated as [16]

$$\mathbf{p}=\mathbf{n}\times\frac{\mathbf{j}}{|\mathbf{j}|}, \tag{3}$$

where $\mathbf{n}$ is the unit normal vector on the metal line surface in direction to the magnetic layer, and $\mathbf{j}$ is charge current density vector.

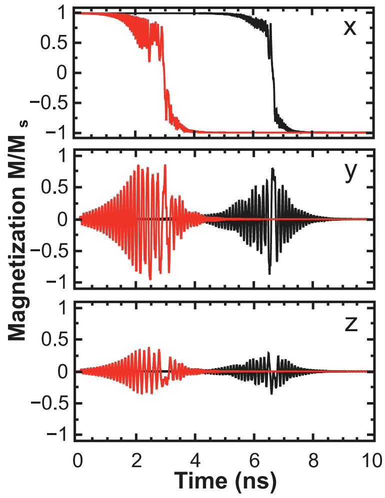

Figure 3. Magnetization components as a function of time: (top) x-component; (middle) y-component; (bottom) z-component. The current is 10μA. The "two write pulses" scheme is shown in red and the single "write pulse 2" scheme is shown in black.

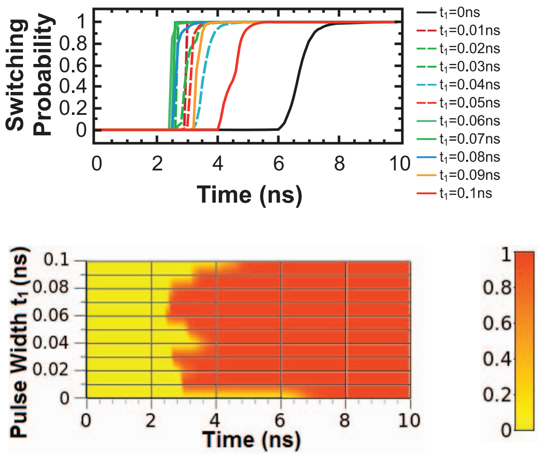

Figure 4. Switching probability for the "two write pulses" scheme as a function of the time for different values of pulse width t_1. For switching probability estimation, 250 simulations of switching were performed on each pulse width t_1.

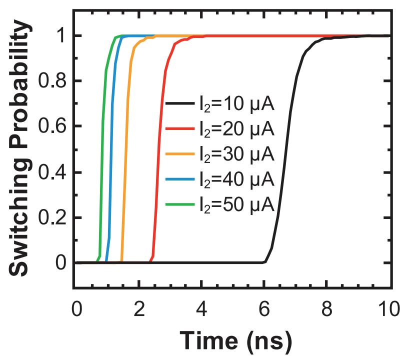

Figure 5. Switching probability for the "write pulse 2" scheme as a function of the pulse duration for five current values. For switching probability estimation, 250 simulations of switching were performed on each current value.

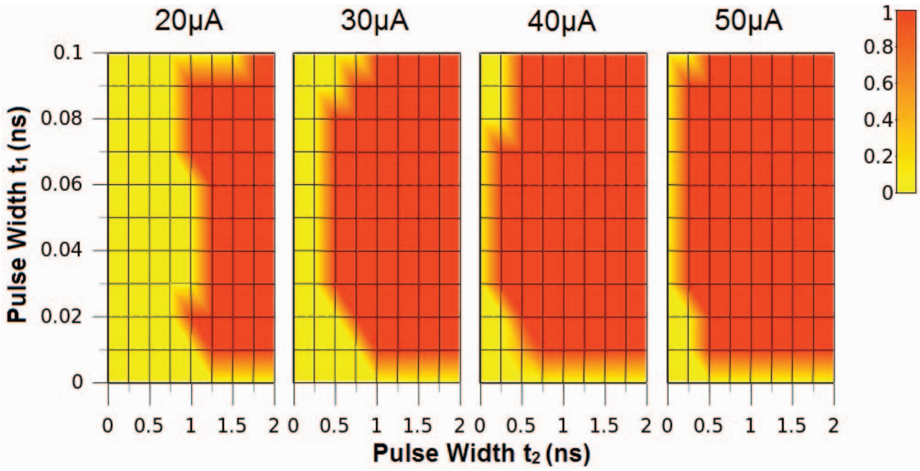

Figure 6. Schematic illustration of the dependence of the switching probability for the “two write pulses” scheme on the current and pulses width. The dependences are shown for four current values: 20μA, 30μA 40μA, and 50μA. For switching probability estimation, 100 simulations of switching were performed on each combination of pulses’ widths.

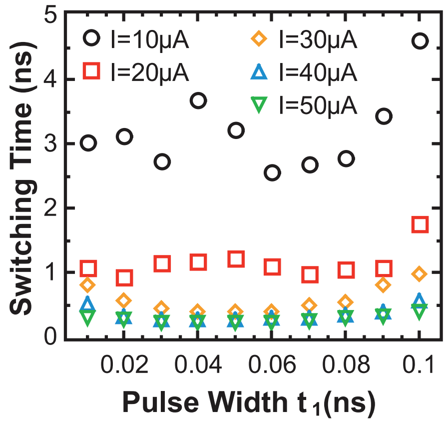

Figure 7. Switching time for the “two write pulses” scheme as a function of the pulse width t_1 for five current values.

The local effective magnetic field is calculated as [17]

$$\mathbf{h}_{\mathbf{eff}} = \mathbf{h}_{\mathbf{ext}} + \mathbf{h}_{\mathbf{ani}} + \mathbf{h}_{\mathbf{exch}} + \mathbf{h}_{\mathbf{demag}} + \mathbf{h}_{\mathbf{th}} + \mathbf{h}_{\mathbf{amp}} + \mathbf{h}_{\mathbf{ms}}, \quad (4)$$

where $\mathbf{h}_{\mathbf{ext}}$ is the external field, $\mathbf{h}_{\mathbf{ani}}$ is the magnetic anisotropy field, $\mathbf{h}_{\mathbf{exch}}$ is the exchange field, $\mathbf{h}_{\mathbf{demag}}$ is the demagnetizing field, $\mathbf{h}_{\mathbf{th}}$ is the thermal field, $\mathbf{h}_{\mathbf{amp}}$ is the Ampere field, and $\mathbf{h}_{\mathbf{ms}}$ is the magnetostatic coupling between the pinned layers and the free layer.

IV. RESULTS AND DISCUSSION

Simulations have been performed for a 52.5×12.5nm^2 CoFeB(2nm) soft layer which is sandwiched between β-Tungsten(3nm) spin Hall metal bar lines (Fig.1a). The other model parameters are: T=300K, M_s=8.9·10^{5}A/m, A=1·10^{-11}J/m, K=2·10^3 J/m^3, α=0.005 [18], and θ_{SHE}=0.3 [19].

To prove the efficiency of the proposed switching method it is necessary to show the absence of switching in the case of using only one from the two pulses, as it is an unwanted event and leads to the loss of information in half-selected cell at the cross-point architecture (Fig.2).

In all our simulations the first pulse width ranges from 0.01 to 0.1ns. These ranges of pulse widths are not sufficient to tilt the magnetization from the initial state by a large enough angle to switch the free layer. Thereby, we examine the switching by two schemes, the single “write pulse 2” and the “two write pulses” scheme. As expected, switching occurs in both cases (Fig.3). But for the “two write pulses” scheme the small initial angle provided by the first pulse leads to a reduction of the second pulse duration required for switching the free layer to a new state. As our simulations show (Fig.4), the switching probability for the proposed “two write pulses” scheme is 1, when the second pulse width ranges from 2.63 to 5.5ns (depending on the first pulse width). These pulse durations are shorter than the respective value of 6ns required to achieve the non-zero switching probability, when the “write pulse 2” scheme is used. This excludes unwanted switching in half-selected cells (for a current of 10μA).

Our simulations show, that in the case of using the “write pulse 2” scheme, the increase of the current leads to a drastic reduction of the switching time (Fig.5). Therefore, we also investigated the influence of the pulse width and the current value on the switching occurrence for the “two write pulses” scheme. Our results indicate that increasing the current value shifts the area where switching is observed towards the region with lower pulse widths (Fig.6) and also leads to a reduced dependence of the switching time on the first pulse width (Fig.7). To note, increasing the current value to 40μA accelerates switching under half a nanosecond (Fig.7 and Fig.8, left) while still preserving half-selected cells from unwanted switching (Fig.8, right), which allows cells sharing the same heavy metal lines and use select transistors (or diodes) only for read operation. Potential memory cell architectures with this switching method are shown in Fig.9.

V. CONCLUSIONS

We demonstrated a new method of soft magnetic layer switching and potential 1Transistor-1MTJ memory cells architectures utilizing this switching method. Our analysis of the proposed method shows a wide range of currents and write pulses’ widths, which could be used for soft magnetic layer switching and do not lead to switching in half-selected cells.

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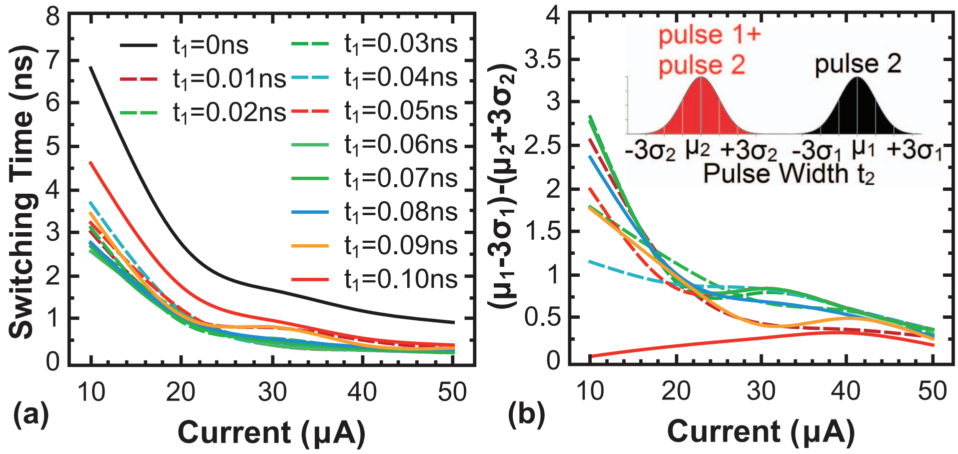

Figure 8. (a) Switching time as a function of current. (b) The difference between the minimum value of the pulse width t_2 required to achieve a non-zero probability of switching by using the "write pulse 2" scheme (μ_1-3σ_1) and a value of the pulse width t_2 needed to achieve guaranteed switching with the "two write pulses" scheme (μ_2+3σ_2) as a function of current.

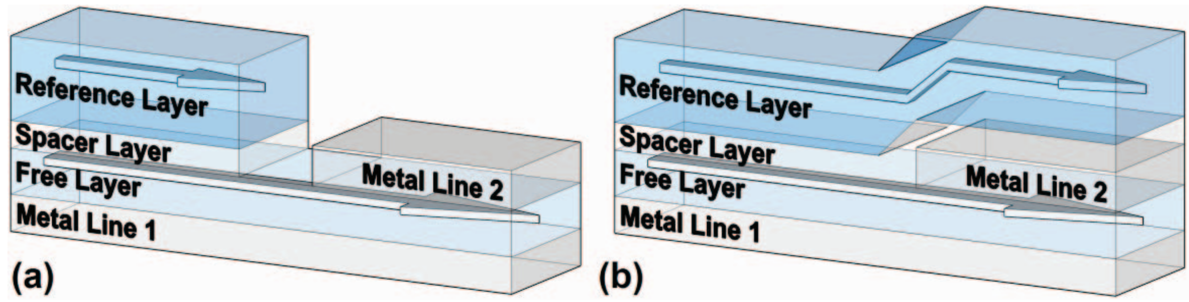

Figure 9. Schematic illustration of two memory cell structures with switching of the free layer based on the proposed "two write pulses" scheme.

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