The Exploitation of Magnetization Orientation Encoded Spin-Transfer Torque for an Ultra Dense Non-Volatile Magnetic Shift Register

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***Abstract*—Nowadays there are two big obstacles for further progress in CMOS device technology. The energy dissipation due to leakage and the energy required to copy information between memory and processor. Even though cutting the power of unused circuits reduces the leakage dissipation to zero, it causes the loss of the locally stored information. Thus, it must be copied back from memory, when the circuit is turned on again. This, unfortunately, degrades the already strained available bandwidth between memory and processor. Using non-volatile elements which can serve as memory and information processing units is an attractive path to overcome these limitations in future computation environments. Therefore, we propose non-volatile circuits based on magnetic flip flops and non-volatile shift registers that extensively exploit these features. For the copy operation of the shift register we have proposed to traverse an unpolarized current through a portion of the read flip flops' free layer to create a spin polarized magnetization orientation encoded current and pass it to a subsequent free layer. There it exerts a spin-transfer torque and switches with the aid of a second clocked spin-transfer torque the subsequent layer. In order to test the feasibility of the operation procedure we reduce the shift register to two flip flops and study all possible input and output combinations via extensive simulations. We found that the switching behaves exactly as required for the proposed copy operation. Thus the feasibility of the operation as well as the operationability of the shift register are demonstrated.**

I. INTRODUCTION

Among the nowadays plentiful obstacles for future progress of CMOS technology, two are currently very prominent. On one hand the power dissipation due to leakage and on the other hand the energy required for the continuous transfer between memory and processors are bottlenecks for further advancements in computing [1], [2]. A simple but very effective solution for the leakage problem is to shut down unused circuit parts. Even though this eliminates the stand by power dissipation, it comes at the price of the dissipation of the locally stored charges and by that the loss of the stored information. Thus, the lost information must be regained when the circuits are powered up again by commonly copying the data back from memory, which degrades the already strained available bandwidth between processors and memory further.

This lead us to the proposal of a non-volatile magnetic flip flop as well as circuits employing them such as a non-volatile magnetic shift register [3] (see Fig. 1) and a non-volatile buffered magnetic logic grid [4] . Due to the avoidance of signal conversion between the CMOS and the magnetic domain and the inherent non-volatility of the employed magnetic layers the proposed circuits exhibit instant-on capabilites, a highly regular structure, a very small layout footprint, and a considerable reduction in the actual information transport due to their non-volatility [4], [5], [6].

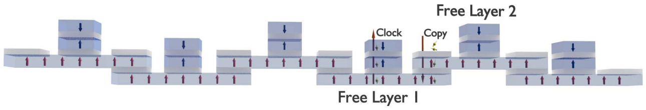

Fig. 1. The non-volatile shift register consists of two rows of non-volatile flip flops that are arranged in two distinct levels. Each free layer of a flip flop overlaps in two regions with its neighbors of the respective other level. The polarizer stack in the middle of the free layers is designated for the application of the clock signals.

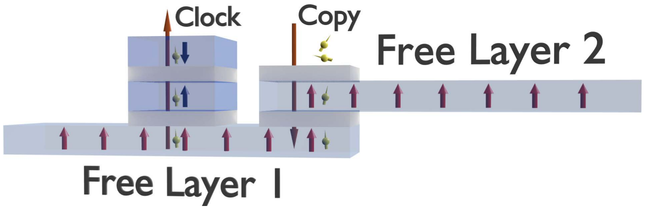

Fig. 2. For the study the n-Bit shift register from Fig. 1 is reduced to two adjacent flip flops. For the copy operation an unpolarized current is traversed through Free Layer 2. The then with the spin orientation from Free Layer 2 encoded polarized current enters Free Layer 1, where the spin-transfer torque acts on the magnetization of the layer. The current pulse through the clock polarizer stack generates a second spin-transfer torque aiding the copy operation by either damping or enforcing the switching of the magnetization in Free Layer 1.

A key ingredient for the operation of the proposed shift register (cf. Fig. 1) and the buffered magnetic logic grid is to read the information stored in a free layer by first traversing an unpolarized current through a portion of the layer to be read and subsequently use the with the magnetization orientation of the read layer encoded spin polarized current to create a spin-transfer torque in the layer to be written into (see Fig. 2). Thus it is possible to directly transfer information between adjacent devices without complex external CMOS circuitry.

Since there is not only a spin-transfer torque generated in the overlapping region of the written device, but also a spin-transfer torque with opposing orientation in the read layer, the magnetization of the read layer can get destabilized and cause read disturbances. Therefore, we added a second synchronously clocked spin-transfer torque contribution to either speed up or damp the switching of the written layer before the read layer gets destabilized and may switch. Up to now

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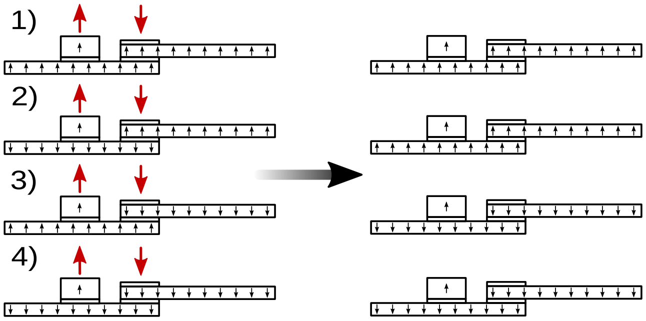

Fig. 3. The 2-Bit shift register is composed of two free layers with two stable magnetization orientations. Thus there are four possible start combinations which require four end combinations for the shift register copy operation.

Parameter	Value
Free layer length	120nm
Free layer width	30nm
Free layer thickness	3nm
Contact size	$30\text{nm} \times 30\text{nm} \times 3\text{nm}$
Magnetization saturation M_S	$4 \times 10^5 \text{A/m}$
Out-of-plane uni-axial anisotropy K_1	10^5J/m^3
Uniform exchange constant A_{exch}	$2 \times 10^{-11} \text{J/m}$
Polarization P, P_1, P_2	0.3
Non-magnetic layer	*Cu*
Gilbert gyromagnetic ratio γ	$2.211 \times 10^5 \text{m/As}$
Damping constant α	0.01
Non-adiabatic contribution ϵ', ϵ_1', ϵ_2'	0.1 [13]
Fitting parameter Λ, Λ_1, Λ_2	2
Discretization length Δx, Δy	3nm
Discretization length Δz	3nm
Discretization time Δt	$1.4875 \times 10^{-14} s$

TABLE I. SIMULATION PARAMETERS

this issue was not analyzed. In this work we investigate the feasibility of the copy operation on a realistic shift register structure.

II. SIMULATION SETUP

In order to reduce the computational effort to a manageable amount, while at the same time incorporating all governing physical effects, and to limit the number of possible input and output combinations a structure of two adjacent flip flops is chosen (see Fig. 2). Assuming that each of the flip flops free layers exhibits two stable magnetic states there are four possible magnetization orientation combinations as shown in Fig. 3. The information is copied from Free Layer 2 into Free Layer 1. The input combinations can be further distinguished into two sets of combinations. For the first set Free Layer 1 and Free Layer 2 possess the same magnetization orientation. Therefore, the desired information is already in Free Layer 1 and the spin-transfer torque from the magnetization orientation encoded polarized current as well as the spin-transfer torque from the clocked spin current must not change the orientation of the free layers. For the second set the magnetization orientation of Free Layer 1 and Free Layer 2 are anti-parallel. In this case the spin-transfer torque caused by the orientation encoded spin current and the spin-transfer torque exerted by the clocked spin current must switch Free Layer 1 before Free Layer 2 is destabilized to such an extent that it may flip.

Each of these combinations has been mapped to the required starting and ending combinations for the desired copy operation (cf. Fig. 3). These cases have been studied separately (cf. Case 1→Fig. 4, Case 2 →Fig. 5, Case 3 →Fig. 6, and Case 4 →Fig. 7).

The free layers are $30\text{nm} \times 120\text{nm} \times 3\text{nm}$ in size and connected by a $30\text{nm} \times 30\text{nm} \times 3\text{nm}$ copper layer. To keep the results comparable to our previous work the same simulation parameters as in [5], [7], [8] have been employed. For a better overview the simulation parameters are also summarized in Tab. I. For each case 101 simulations including thermal excitations were carried out. The two synchronous current pulses required for the copy operation (positive for copying and negative for the clock, cf. Fig. 2) have been fixed at $2 \times 10^{11} \text{A/m}^2$ and 2ns pulse length.

III. THEORY

The dynamics of the studied non-volatile magnetic flip flops is governed by the Landau-Lifshitz-Gilbert equation [9], [10] supplemented with several spin-transfer torque terms:

$$\frac{\mathrm{d}}{\mathrm{d}t}\vec{m} = \gamma\left(-\vec{m}\times\vec{H}_{\text{eff}} + \alpha\left(\vec{m}\times\frac{\mathrm{d}}{\mathrm{d}t}\vec{m}\right) + \vec{T}_{\text{clock}} + \vec{T}_1 + \vec{T}_2\right) \tag{1}$$

with $\vec{m}$ describing the reduced magnetization, γ the electron gyromagnetic ratio, α the dimensionless damping constant, and $\vec{H}_{\text{eff}}$ the effective field. $\vec{H}_{\text{eff}}$ is calculated from the functional derivative of the free energy density. Energy contributions from the uni-axial anisotropy, exchange, demagnetization, and thermal excitations [11] have been considered.

The precessional motion due to the effective magnetic field $\vec{H}_{\text{eff}}$ is covered by the first term in (1). A power dissipation proportional to $\frac{\mathrm{d}}{\mathrm{d}t}\vec{m}$ is described by the second term and the last three terms take care of the acting spin-transfer torques. Since the non-magnetic layers are made out of copper, the amplitude and angle dependence of the spin-transfer torques are expressed by the model from Xiao [12]. Thus the spin-transfer torque model for the region of Free Layer 1 below the clocked contact looks like:

$$\vec{T}_{\text{clock}} = \frac{\hbar}{\mu_0 e}\frac{J_{\text{clock}}}{l_1 M_S}\frac{P\Lambda^2}{(\Lambda^2+1)+(\Lambda^2-1)\,\vec{m}_1\cdot\vec{p}}\,\cdot \\ \cdot\left(\vec{m}_1\times\vec{p}\times\vec{m}_1+\epsilon'\vec{m}_1\times\vec{p}\right) \tag{2}$$

$\hbar$ describes the Planck constant, μ_0 the magnetic permeability, J_{clock} the applied current density, l_1 the thickness of Free Layer 1, M_S the magnetization saturation, P the spin current polarization, $\vec{p}$ the unit polarization direction of the polarized current, and Λ a fitting parameter handling non-idealities. The spin-transfer torque model for spin valves exhibits an in-plane ($\vec{m}_1\times\vec{p}\times\vec{m}_1$) and a small out-of-plane component ($\vec{m}_1\times\vec{p}$) [13].

The second spin-transfer torque contribution to Free Layer1 $\vec{T}_1$ is due to the spin valve stack formed by the overlap between Free Layer 1 and Free Layer 2 (see Fig. 2). Also here a copper interface was chosen and the model described in [12] is applicable. However, in this case the reduced magnetization of Free Layer 2 $\vec{m}_2$ acts as the unit polarization direction, since the electrons get polarized in Free Layer 2 before entering into Free Layer 1. Hence $\vec{p}$ from (1) is replaced by $\vec{m}_2$ [14]:

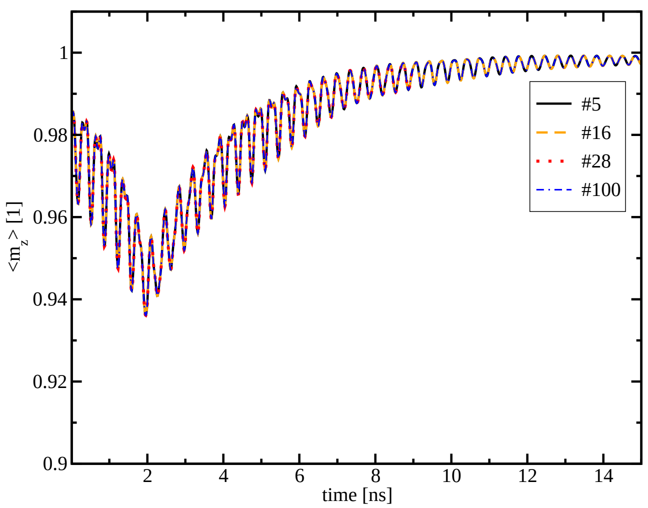

Fig. 4. For Case 1 depicted in Fig. 3, the total averaged and normalized z-component of the magnetization as a function of time $<m_z(t)>$ is shown. In this case the magnetization of both layers points initially towards the positive z-axis and must not change during the operation.

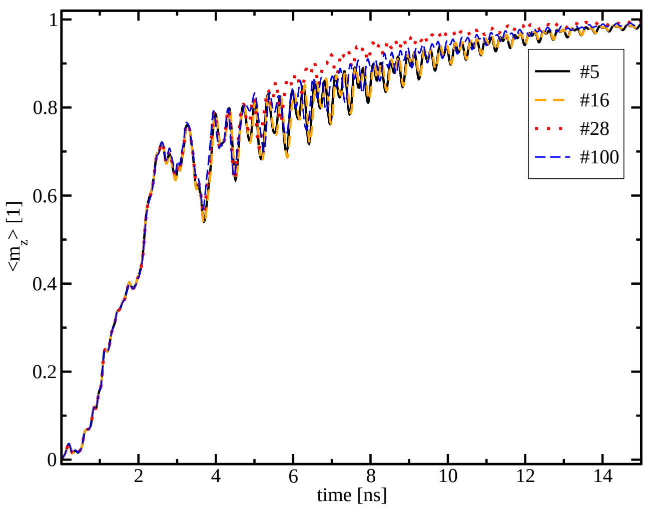

Fig. 5. For Case 2 (cf. Fig. 3) the magnetization of Free Layer 1 points towards the negative z-axis and the magnetization of Free Layer 2 towards the positive z-axis. After the operation the magnetization of both free layers must be oriented upwards.

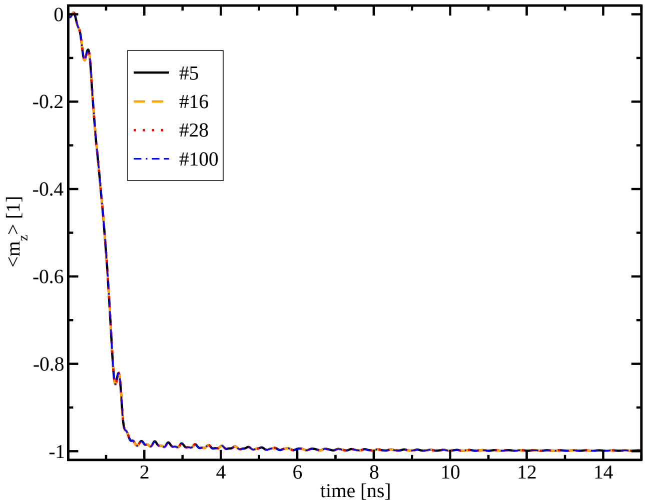

Fig. 6. For Case 3 the initial magnetization orientation of Free Layer 1 is oriented along the positive z-axis and the magnetization orientation of Free Layer 2 is pointing along the negative z-axis. Both free layers must be oriented along the negative z-axis after the copy operation.

$$\begin{aligned}\vec{T}_1 = \frac{\hbar}{\mu_0 e}\frac{J_{\text{copy}}}{l_1 M_S}\frac{P_1\Lambda_1^2}{(\Lambda_1^2+1)+(\Lambda_1^2-1)\,\vec{m}_1\cdot\vec{m}_2}\cdot \\ \cdot\left(\vec{m}_1\times\vec{m}_2\times\vec{m}_1+\epsilon_1'\vec{m}_1\times\vec{m}_2\right)\end{aligned} \tag{3}$$

J_{copy} denotes the applied current density, P_1 describes the spin current polarization, Λ_1 the fitting parameter for non-idealities, and ϵ_1' the out-of-plane torque strength for Free Layer 1 at the overlapping region.

The third spin-transfer torque $\vec{T}_2$ acts on Free Layer 2, when a current is pushed through the region where both free layers overlap. Since Free Layer 2 shares the copper interface with Free Layer 1, again the model described in [12] is employed. This torque acts with the opposite orientation of spin-transfer torque $\vec{T}_1$ and the magnetization orientation of Free Layer 1 is used as unit polarization direction $\vec{p} \rightarrow \vec{m}_1$ [14]:

$$\begin{aligned}\vec{T}_2 = -\frac{\hbar}{\mu_0 e}\frac{J_{\text{copy}}}{l_2 M_S}\frac{P_2\Lambda_2^2}{(\Lambda_2^2+1)+(\Lambda_2^2-1)\,\vec{m}_2\cdot\vec{m}_1}\cdot \\ \cdot\left(\vec{m}_2\times\vec{m}_1\times\vec{m}_2+\epsilon_2'\vec{m}_2\times\vec{m}_1\right)\end{aligned} \tag{4}$$

Furthermore, it has been assumed that in the overlapping region the applied current density J_{copy} is the same for both layers. l_2 denotes the thickness, P_2 describes the spin current polarization, Λ_2 the fitting parameter for non-idealities, and ϵ_2' the out-of-plane torque strength for Free Layer 2 at the overlapping region.

IV. RESULTS AND DISCUSSION

The time dependent evolution of the total averaged and normalized z-component of the magnetization for the four different input combinations is shown in Fig. 4, Fig. 5, Fig. 6, and Fig. 7. Due to the very narrow curve distribution between the curves, only four curves out of the full data set are depicted (samples #5, #16, #28, and #100) to keep the individual curves recognizable. The four cases can be divided into two sub groups. For the first group Free Layer 1 and Free Layer 2 posses the same magnetization orientation before the operation (Case 1→Fig. 4 and Case 4→Fig. 7). In these cases the information to be copied from Free Layer 2 is already stored in Free Layer 1. Thus, the applied pulses for operation must not change the free layer's magnetization orientation. The positive current polarity through the overlapping region creates a spin-transfer torque in Free Layer 1 which pushes the local magnetization into its current position and stabilizes the magnetization orientation. For the region where the clocked spin-transfer torque is applied one has to distinguish between Case 1 and Case 4. In Case 1 the negative current exerts a spin-transfer torque which tries to flip the local magnetization downwards, while for Case 4 the local magnetization is already pointing down and thus the torque acts stabilizing. We attribute the slight difference in the amount of the free layer excitation between Fig. 4 and Fig. 7 to this. Nevertheless, in both cases the torque in Free Layer 2 facilitates excitations, but since it

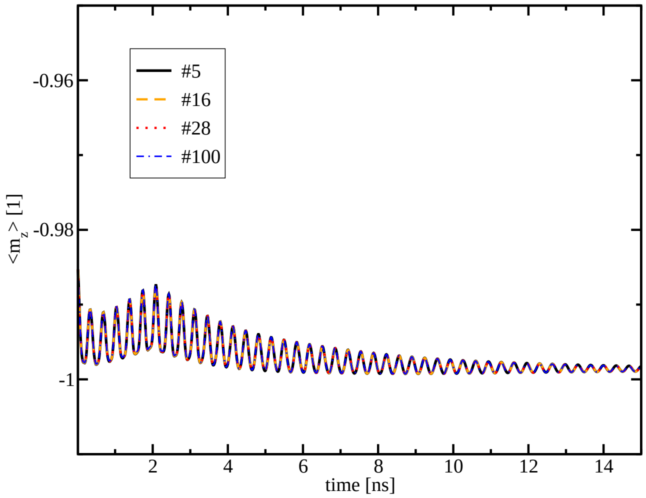

Fig. 7. For Case 4 initially both free layers point along the negative z-axis and must not change during the copy operation.

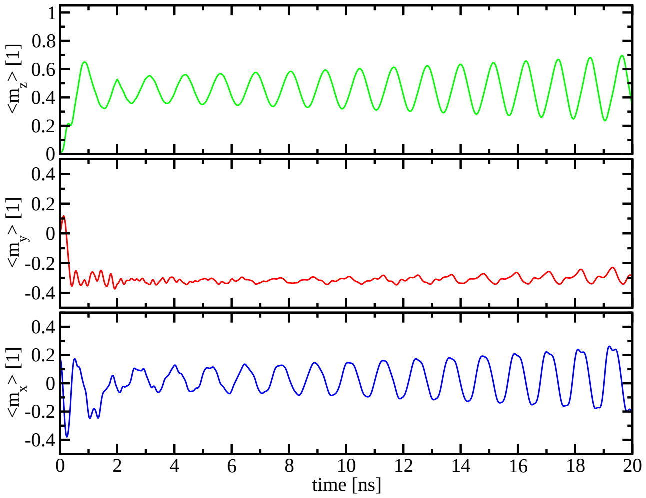

Fig. 8. Example for the formation of an oscillating domain wall for both current pulses with positive polarity, and initially anti-parallel oriented free layers.

takes much longer than the chosen $2\mathrm{ns}$ to excite Free Layer 2 enough to cause flipping, the layer orientation does not change.

For the second group Free Layer 1 and Free Layer 2 are initially anti-parallel (Case 2→Fig. 5 and Case 3→Fig. 6). The spin-transfer torque generated by the positive pulse through the overlapping region tries to switch the magnetization to the same orientation as in Free Layer 2. The observed difference in switching times between Case 2 shown in Fig. 5 and Case 3 shown in Fig. 6 can be explained by the difference in the onset torque for parallel and anti-parallel orientation between the local magnetization $\vec{m}_1$ and the unit polarization direction $\vec{p}$ from the clocking stack. Due to the negative sign of the clock pulse, parallel orientations between $\vec{m}_1$ and $\vec{p}$ cause a torque striving to speed up the switching process (cf. Case 3), while for an initially anti-parallel orientation the created torque damps the switching process (Case 2). This is also reflected in the calculated average switching times and their standard deviation, which are $1.42\mathrm{ns} \pm 0.01\mathrm{ns}$ and $7.2\mathrm{ns} \pm 0.61\mathrm{ns}$, respectively. Additionally we found for certain polarity and current density combinations an oscillating domain wall in Free Layer 1. These oscillations could be be harnessed for (coupled) nano-scale spin-transfer torque oscillators (see Fig. 8).

V. CONCLUSION

Summarizing our findings, we conclude that for all four input combinations the proposed copy operation leads to the desired end combinations. Thus, not only the feasibility of the copy operation is shown, but also the full functionality of the non-volatile shift register is demonstrated. These findings pave the way towards more complex CMOS compatible circuits for non-volatile computing.

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