Analysis of a spin-transfer torque based copy operation of a buffered magnetic processing environment

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ABSTRACT

The static power dissipation and the communication bandwidth between memory and processors have become performance limiting bottlenecks for modern computer systems. The introduction of certain nonvolatile devices, i.e. magnetic tunnel junctions (MTJ), enables the realization of fast zero standby power and instant-on CMOS/MTJ hybrids. However, these solutions still cannot compete with pure CMOS circuits in one of the key aspects, namely integration density. In order to circumvent this limitation, we suggested to move as much as possible of the CMOS functionality into the magnetic domain. As a result, we proposed a nonvolatile magnetic processing environment where information encoded spin-transfer torques perform instructions. In this work we investigate the copy operation which is essential for the magnetic processing environment. In particular, we analyze geometry dependences and misalignment issues for the fabrication process.

Keywords: spin-transfer torque, nonvolatile computing, buffered magnetic processing environment, misalignment, geometry dependence

1. INTRODUCTION

For many decades, progress in CMOS technology was accompanied by solving tough problems. Today the two most performance limiting bottlenecks are the power dissipation due to leakage and the energy spent for the continuous information transport between the physically separated memory and the processors [1], [2]. To circumvent the limitations due to the heat generation by the dissipated energy, usually idle circuit parts are shut down. However, this comes at the price of losing the information stored by leakage. Therefore, when a circuit is brought online again, all lost information must be recovered by copying the information back from memory, before the actual operation can start. This puts additional load on the communication between the already strained bandwidth between memory and processors. In order to resolve this issue one has to introduce nonvolatile elements close to the circuits, where the information is needed, when woken up. Spin electronics (spintronics) is very appealing for this task. Spintronic devices are nonvolatile, operate very fast, and offer high endurance [3]. Indeed, the introduction of certain spintronic devices, i.e. magnetic tunnel junctions (MTJ), into CMOS technology shows first commercially available magneto-resistive random access memory (MRAM) and embedded DRAM products, and even more innovations will surely follow soon [4], [5], [6].

Even though several competitive solutions for nonvolatile logic already exist, they are not competitive with respect to one of the key aspects of CMOS technology, namely their integration density. This stems from the fact that these CMOS/MTJ hybrid structures employ MTJs only as auxiliary storage. The actual computation is still performed by CMOS transistors. To make things worse, the introduction of MTJs into the circuits requires extra transistors to read and write their state, which increases the circuit complexity and the footprint of the overall circuit [1], [7].

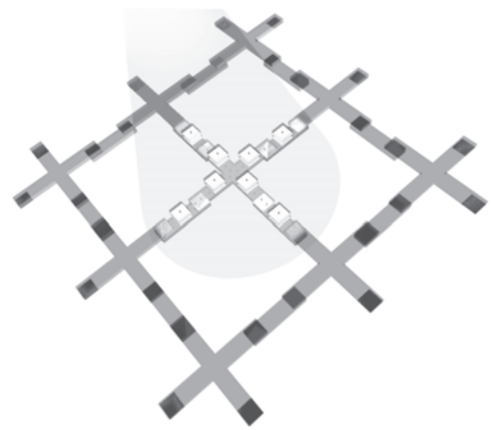

Fig. 1 The proposed buffered magnetic processing environment combines spin-transfer torque majority gates (crosses) and flip flops (rectangles). The majority gates perform the calculation, while the flip flops act as shared buffers.

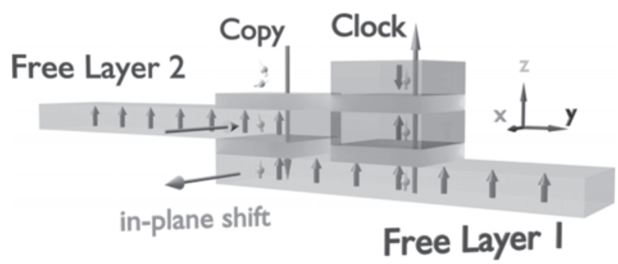

Fig. 2 For our study we investigated a two-bit shift register. It comprises two adjacent magnetic free layers which are electrically connected by a copper layer. The information stored in Free Layer 2 is copied into Free Layer 1 by first passing a current through Free Layer 2. During the passage through Free Layer 2 the electrons' magnetic moment orients parallel to Free Layer 2 and, when the electrons finally enter into Free Layer 1, they relax to the local magnetization orientation. This creates a spin-transfer torque which is encoded with the magnetization orientation of Free Layer 2. This torque acts on Free Layer 1 and tries to orient it parallel to Free Layer 2. In order to facilitate the information copy to Free Layer 1 while preventing Free layer 2 from error switching due to back-action, a second synchronous clock spin-transfer torque acting on Free Layer 1 is added.

Therefore, we came up with the idea of avoiding the signal conversion between the magnetic and the CMOS domain and to put as much as possible functionality into the magnetic domain. The consequent avoidance of transistors led us to propose a

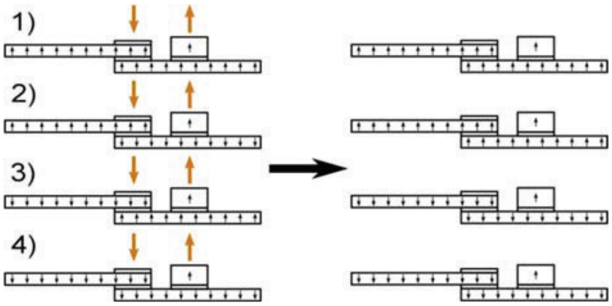

Fig. 3 The two free magnetic layers exhibit two perpendicular stable states. For each of the four possible input combinations there is a unique output combination after the copy operation has been applied.

Parameter	Value
Free layer length	120nm
Free layer width	30nm
Free layer thickness	3nm
Free layer shift	0, 2, 3, 5nm
Magnetization saturation M_S	4×10^5 A/m
Out-of-plane uni-axial anisotropy K_1	10^5 J/m^3
Uniform exchange constant A_{exch}	2×10^{-11} J/m
Polarization P	0.3
Non-magnetic layer material	Cu
Gilbert gyromagnetic ratio γ	2.211×10^5 m/As
Damping constant α	0.01
Non-adiabatic contribution ε'	0.1
Fitting parameter Λ	2
Discretization length Δx, Δy	2, 3, 5nm
Discretization length Δz	3nm
Discretization time Δt	1.4875×10^{-14} s

Tab. 1 Simulation parameters

buffered magnetic processing environment (see Fig. 1) [8], a nonvolatile shift register [9], as well as a nonvolatile flip flop [10], and a nanoscale spin-transfer torque oscillator [11]. Avoiding signal conversion is important, but the fact that the information must be processed and moved still remains. Therefore, we suggested to exploit the spin-transfer torque effect for copying information between adjacent layers, cf. Fig. 3. By pushing an initially unpolarized current through the layer to be read, the traversing electrons will align their magnetic moment parallel to the layers' magnetization. If these electrons now enter the layer to be written, they will relax and create an orientation encoded spin-transfer torque on the local magnetization of the subsequent layer. This torque is able to copy the information stored from the previous layer. Since the polarization of the electrons in the read layer also causes a spin-transfer torque, the read layer could get excited to a point where it might flip and cause a read error. In order to speed up the writing operation, while keeping the read layer stable, we proposed to add a second spin-transfer torque that acts only on the written layer. Extensive simulation studies showed that the concept works, but it also revealed a dependence on the acting stray field strength in the overlapping regions [12]. Due to fluctuating conditions during the manufacturing process there will be always a certain amount of variability in the free layers' alignment. These variations will have an important impact on the proposed copy operation. In this work we investigate how in particular the in-plane misalignment influences the copy operation.

2. SIMULATION SETUP

For our analysis we chose the Landau-Lifshitz-Gilbert equation [13] to describe the dynamics of the magnetic layers and added spin-transfer torque terms [14], [15] to incorporate the effect of the acting polarized currents. To keep the number of switching combinations under investigation and the computational effort on a reasonable level, a two-bit shift register consisting of two adjacent magnetic free layers was assumed (cf. Fig. 2 and Fig. 3). Each free layer exhibits two stable magnetization states along their perpendicular axis and thus there are four possible combinations in total. It was further assumed that the information is copied from Free Layer 2 (only Copy) into Free Layer 1 (Copy and Clock). In order to create the logic table of a shift register which always copies the information from Free Layer 2 into Free Layer 1, there are four well defined final combinations for each initial combination (see Fig. 3). These combinations can be further distinguished into one subset, where Free Layer 1 and Free Layer 2 possess the same magnetization orientation (Case 1 and Case 4), and one subset, where Free Layer 1 and Free Layer 2 exhibit anti-parallel orientations (Case 2 and Case 3). In the first subset neither the torques acting on Free Layer 1 nor the torque acting on Free Layer 2 must change the magnetization states. For the second set Free Layer 1 and Free Layer 2 posses opposing magnetization orientations (Case 2 and Case 3). In these cases, the orientation encoded spin-transfer torques from the Copy pulse and the Clock pulse must switch the magnetization orientation of Free Layer 1 before Free Layer 2 is excited to an extent where read errors occur. The copy operation has been simulated for Case 1 to Case 4 independently (cf. Fig. 4 to Fig. 7 for Case 4, Fig. 8 to Fig. 11 for Case 2, and Fig. 12 to Fig. 16 for Case 3). Since thermal excitations were considered, the switching of the free layers shows statistical fluctuations. In order to account for these, for each case and layer misalignment, the copy operation with 101 random realizations of statistical fluctuations at 300K was simulated. The curves shown in Fig. 4 to Fig. 15 depict the mean value μ for the total normalized and averaged magnetization along the z-axis $\langle m_z \rangle$ over all samples at each time step. Additionally also the respective envelope curves $\mu \pm \sigma$ are shown, where σ is the respective standard deviation, to give the reader some idea about the distribution width. However, Fig. 16 depicts three exemplary individual $\langle m_z \rangle$ curves out of the 101 samples to elucidate the reason for the rather broad distribution width found in Fig. 15 in comparison to the other figures. Furthermore, to keep the results comparable to earlier simulation studies, the same parameters and free layer size (30nm×120nm×3nm) as in [12] and [16] where chosen. It has been assumed that the interconnecting metal has been made out of copper and that only the region, where both layers intersect, and the clock region carry a current. Thus, only these two regions experience spin-transfer torques to mimic manufacturing related misalignment. The free layers were shifted with respect to each other along the x-axis between zero, 2nm, 3nm, and 5nm. The copy operations were performed by applying two synchronous 2ns long current pulses with an amplitude of 2×10^{11}A/m^2. The copy pulse direction was defined as positive and the clock pulse as negative (see Fig. 2). The simulation parameters are summarized in Tab. 1.

3. RESULTS AND DISCUSSION

The simulations for the first subset of cases (Case 1 and Case 4), where before and after the operation the magnetization states must not change, showed that the pulse length is sufficiently short to prevent an undesired switching event. Fig. 4, Fig. 5, Fig. 6, and Fig. 7 depict Case 4 for different free layer misalignments. The figures start at a value close to -1 for $\langle m_z \rangle$, since for Case 4 in both free layers the magnetization points against the z-axis. For all free layer misalignments the

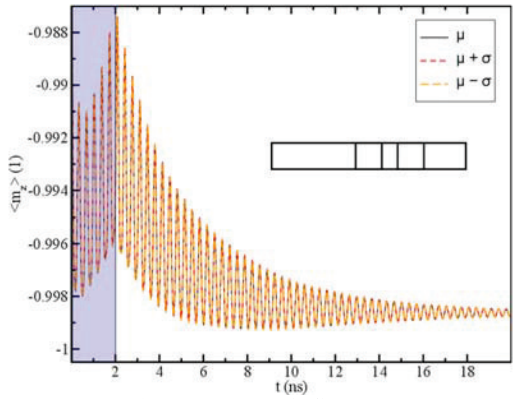

Fig. 4 Case 4: no misalignment

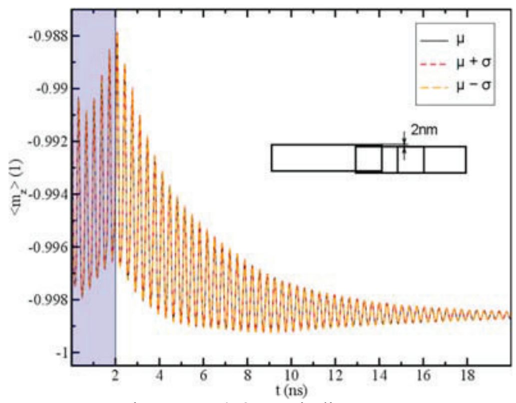

Fig. 5 Case 4: 2nm misalignment

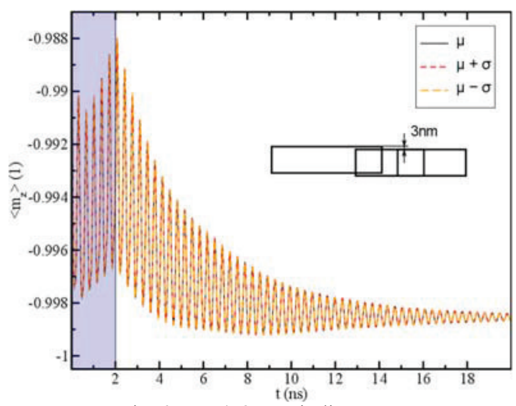

Fig. 6 Case 4: 3nm misalignment

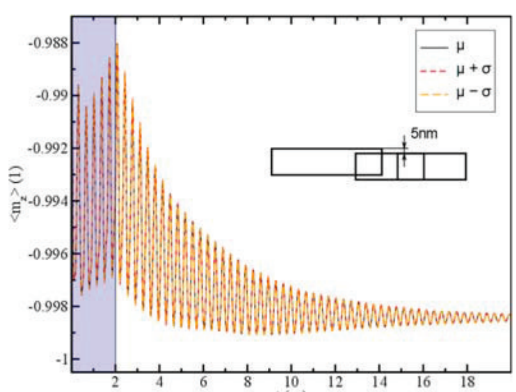

Fig. 7 Case 4: 5nm misalignment

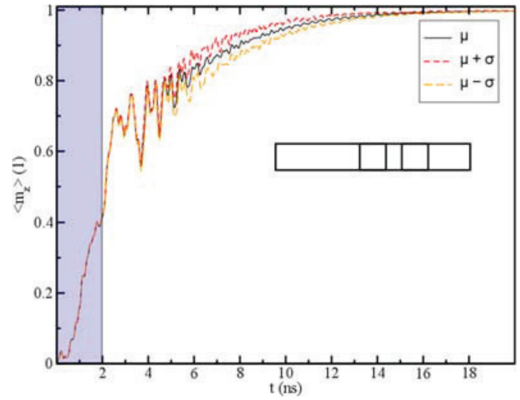

Fig. 8 Case 2: no misalignment

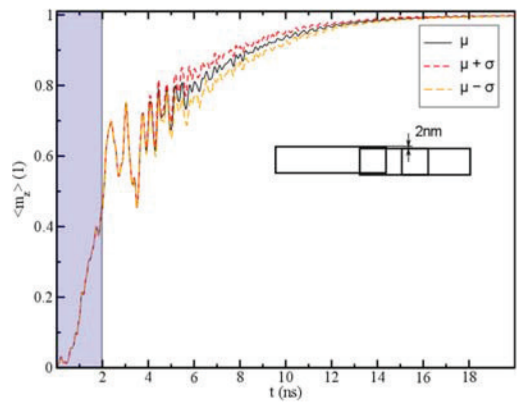

Fig. 9 Case 2: 2nm misalignment

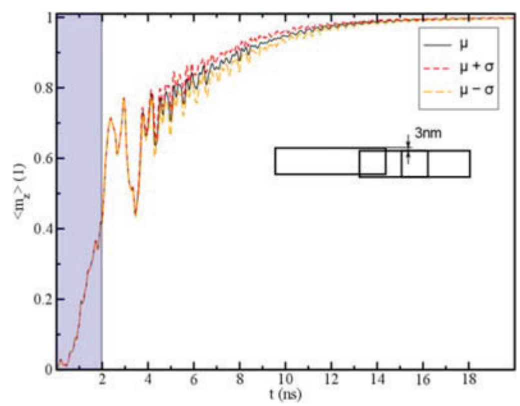

Fig. 10 Case 2: 3nm misalignment

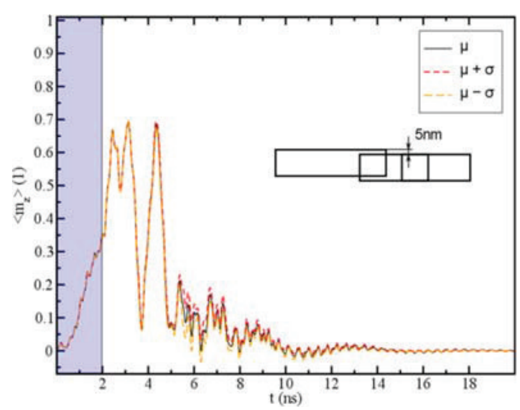

Fig. 11 Case 2: 5nm misalignment

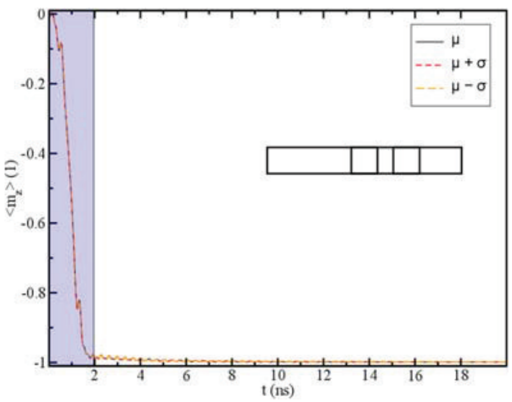

Fig. 12 Case 3: no misalignment

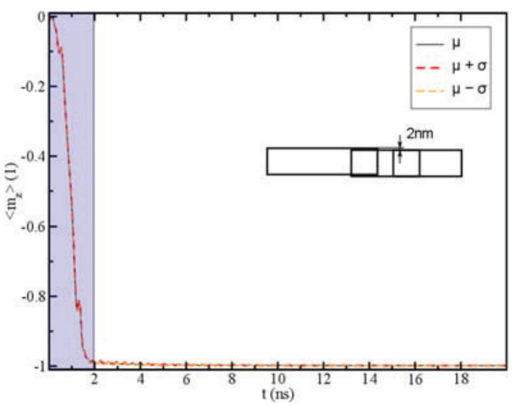

Fig. 13 Case 3: 2nm misalignment

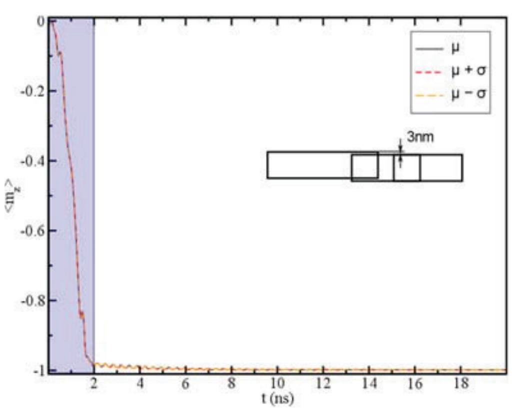

Fig. 14 Case 3: 3nm misalignment

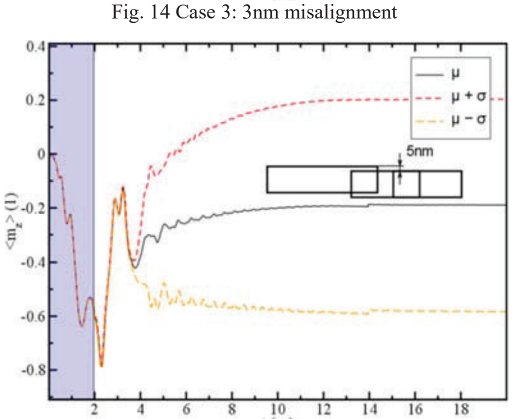

Fig. 15 Case 3: 5nm misalignment

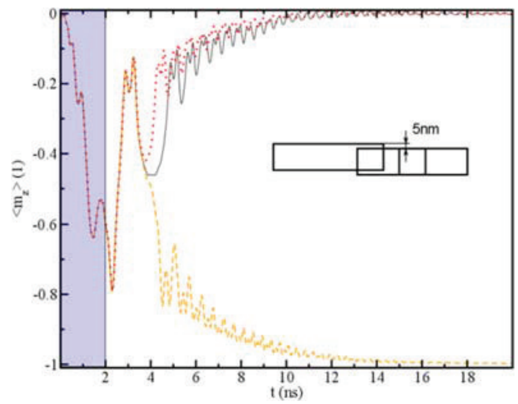

Fig. 16 Case 3: 5nm misalignment (three individual samples)

magnetization excitation during the 2ns pulses is only small (the blue boxes show the time when the pulses are active) and there is a slight trend towards smaller excitations for increasing shifts. The simulations for Case 1 behave exactly the same way and are therefore omitted. We attribute this effect to the shrinking of the overlapping area for increasing misalignments and the thereby reduced acting torque in the free layer. For the second subset (Case 2 and Case 3) with initially anti-parallel magnetization states, the copy operation from Free Layer 1 into Free Layer 2 works until a relative layer misalignment of 3nm is reached (see Fig. 8, Fig. 9, Fig. 10, and Fig. 11). Here, the figures start at a value close to 0, since for Case 2 the magnetization in Free Layer 1 points down and in Free Layer 2 points up in relation to the z-axis, and must converge towards +1 to end up in a configuration where it points up in both layers. As can be seen from Fig. 11 at a misalignment of 5nm the acting torques are not sufficient anymore to switch the magnetization in Free Layer 1. The corresponding switching times and probabilities for zero, 2nm, 3nm, and 5nm misalignment are 7.2ns ±0.61ns (100%), 7,87ns ±0.35ns (100%), 7.42ns ±0.46ns (100%), and 9.49ns ±0.01ns (0.99%), respectively. Fig. 12, Fig. 13, Fig. 14, and Fig. 15 show Case 3 and start again at $<m_z>=0$ (anti-parallel layers), but must converge towards -1 to ensure that the down state from Free Layer 2 is copied into Free Layer 1. The convergence of the mean value μ towards -0.2 and the rather big standard deviation σ of ≈0.4 in Fig. 15 suggests that the switching becomes random and thus fails. Fig. 16 depicts three exemplary samples $<m_z>$ and confirms the switching failure, but also reveals that both free layers always relax to an parallel upward or downward position. For Case 3 the switching times and probabilities for zero, 2nm, 3nm, and 5nm misalignment are 1.42ns ±0.01ns (100%), 1.43ns ±0.06ns (100%), 1.58ns ±0.04 (100%), and 6.92ns ±0.19ns (19.8%), respectively. Increasing the free layer misalignment reduces the acting torque and causes a slow down and broadening of the switching distribution. At 5nm the acting torque is not sufficient anymore to push the free layer magnetization reliably into the downward position and small thermal fluctuations decide into which state it will relax. The differences in switching behavior between Case 2 and Case 3 can be explained by the difference in the torque direction for the current flow relative to the magnetization orientation. While for Case 3 the spin-transfer torques enforce each other, for Case 2 they counter act and damp the precessions necessary for switching.

4. CONCLUSIONS

The proposed buffered magnetic environment can tolerate slight in-plane misalignments of the magnetic layers. The different behavior in the various cases can be attributed to the differences in the acting torque directions and the thereby enforced or damped switching.

5. ACKNOWLEDGMENT

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6. REFERENCES

[1] W. Zhao et al., "Design of MRAM based logic circuits and its applications", **in Proc. ACM Great Lakes Symposium on VLSI**, 2011, pp. 431-436.

[2] R. Marculescu et al., "Outstanding research problems in NoC design: System, microarchitecture, and circuit perspectives", **IEEE Trans.Computer-Aided Design of Integrated Circuits and Systems,** Vol. 28, No. 1, 2009, pp. 3-21.

[3] D. Nikonov et al., "Overview of beyond-CMOS devices and a uniform methodology for their benchmarking", **in Proc. IEEE**, Vol. 101, No. 12, 2013, pp. 2498-2533.

[4] Everspin Technologies, http://www.everspin.com/pub, 2016.

[5] T. Hanyu et al., "Standby-power-free integrated circuits using MTJ-based VLSI computing", **in Proc. IEEE**, Vol. 104, No. 10, 2016, pp. 1844-1859.

[6] Y. Fan et al., "Spintronics Based on Topological Insulators", **SPIN**, Vol. 6, No. 2, 2016, pp. 1640001-1─1640001-13

[7] D. Chabi et al., "Ultra low power magnetic flip-flop based on checkpointing/power gating and self-enable mechanisms", **IEEE Trans.Circuits and Systems I: Fundamental Theory and Applications**, Vol. 61, No. 6, 2014, pp. 1755-1765.

[8] T. Windbacher et al., "Novel buffered magnetic logic gate grid", **in Silicon Compatible Materials, and Technologies for Advanced Integrated Processes, Circuits and Emerging Applications 5**, The Electrochemical Society, 2015, pp. 295-303.

[9] T. Windbacher et al., "Novel MTJ-based shift register for nonvolatile logic applications", **in Proc. IEEE/ACM International Symposium on Nanoscale Architectures**, 2013, pp. 36-37.

[10] T. Windbacher et al., "Rigorous simulation study of a novel nonvolatile magnetic flip flop", **in Proc. International Conference on Simulation of Semiconductor Processes and Devices**, 2013, pp. 368-371.

[11] T. Windbacher et al., "Novel bias-field-free spin transfer oscillator", **Journal of Applied Physics,** Vol. 115, No. 17, 2014, pp. 17C901-1─17C901-3.

[12] T. Windbacher et al., "The exploitation of magnetization orientation encoded spin-transfer torque for an ultra dense non-volatile magnetic shift register", **in Proc. 46th European Solid State Device Research Conference**, 2016, pp. 311-314.

[13] H. Kronmüller, **Handbook of Magnetism and Advanced Magnetic Materials: General Micromagnetic Theory**, John Wiley & Sons, Ltd, 2007.

[14] J. Xiao et al., "Boltzmann test of Slonczewski's theory of spin-transfer torque", **Physical Review B**, Vol. 70, 2014, pp. 172405.

[15] T. Moriyama et al., "Phase locking and frequency doubling in spin-transfer-torque oscillators with two coupled free layers", **Physical Review B**, Vol.86, 2012, 060411.

[16] T. Windbacher et al., "Influence of magnetization variations in the free layer on a non-volatile magnetic flip flop", **Solid-State Electronics**, Vol. 108, 2015, pp. 2-7.