# Influence of Magnetization Variations in the Free Layer on a Non-Volatile Magnetic Flip Flop

Thomas Windbacher, Hiwa Mahmoudi, Viktor Sverdlov, and Siegfried Selberherr
Institute for Microelectronics, TU Wien, Gußhausstraße 27–29/E360, A-1040 Vienna, Austria
Email: {windbacher|mahmoudi|sverdlov|selberherr}@iue.tuwien.ac.at

***Abstract*—Recently, we proposed an alternative non-volatile magnetic flip flop which allows high integration density. This work extends the up to now gained results to the devices' functionality under statistically distributed magnetization variations of its free layer. Assuming position uncorrelated random fluctuations in the free layer, that the variations are fixed with respect to time, and that small deviations from its mean are more likely than big ones, a Gaussian distribution was chosen to model the random fluctuations. The random variations were added to the simulations as a position dependent Zeeman term and their influence was varied by changing the variance of the distribution scaled in percent of the free layers saturation magnetization. The results show that the flip flop is capable of operating under high free layer variations.**

***Index Terms*—spintronic, flip flop, spin transfer torque, layer magnetization variations**

## I. Introduction

Since its very beginnings the semiconductor industry was driven to push the achievable integration density to reduce costs and satisfy the demand for cheap and powerful electronics. This is reflected in the ITRS [1], however, over the years each technology node becomes significantly more expensive and it gets harder to keep control over the CMOS devices. Therefore, in the past new processes, materials, and devices have been introduced several times, e.g., global and local strain techniques, high-k metal gate stacks, 3D FETs. As technology evolved new possible show stoppers like interconnection delay and the devices power consumption appeared [2], [3]. This led to the idea to move from normally "ON" circuits and devices to normally "OFF" designs, where latent circuit parts are shut down completely and power will only be consumed, when information is read, written, or processed. The switch from permanently dissipating power systems to only when required spending energy systems demands a reevaluation of all CMOS building blocks. Here, spin as a degree of freedom and its advantageous features like non-volatility, high endurance, and fast operation attract special attention [4]. Besides the self-evident exploitation of spintronics for memory applications, the use of spin also allows to perform logic operations and information transport differently than in state of the art CMOS applications [5], [6]. Hence, the paradigm of the von Neumann architecture and its disadvantages, like the performance limiting information transport between memory and processing units through a common bus, can be eased and may become superfluous in the future. Additionally, merging memory and computation units promises a further boost in integration density.

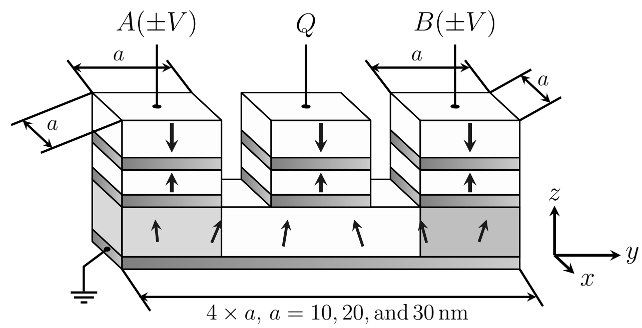


Fig. 1. Proposed non-volatile magnetic flip flop. $A$ and $B$ denote the inputs for the two spin valve stacks and $Q$ denotes the output for the readout stack. The common shared free layer mediates the excited spin precessions. The excited precessions either enforce the switching of the free layer (identical pulse polarities) or quench the switching (opposing pulse polarities). Thus, the flip flop offers SET, RESET, and HOLD operations.

While spintronic memory applications have become so mature that they start to penetrate the market [7], [8], [9], [10], other utilizations are still in the experimental or even conceptual phase [4]. However, not only memory and combinational logic needs a redesign, also sequential logic, e. g. flip flops and latches, requires reconsideration. Even though, there are already non-volatile spintronic flip flops, they are commonly built as CMOS magnetic tunnel junction (MTJ) hybrids [2]. The results are promising with respect to power consumption and speed, but due to the need to convert the signal between the spintronics signal domain (memory) and CMOS domain (computation) every time information is read, written, or processed, additional transistors are necessary which rather decrease the integration density than clears die space [2].

## II. Device and Operation Principle

Therefore, we proposed a non-volatile magnetic flip flop which shifts the actual computation from the CMOS domain to the magnetic domain [11], [12]. Thus, one is able to harvest the benefits of spintronics and at the same time denser and simpler layouts are enabled. The structure comprises three anti-ferromagnetically coupled stacks, two for input $A$ and $B$ and one for readout $Q$. Each stack features an out-of-plane anisotropy and is connected to the common free layer by a spin barrier (e.g. copper or $\mathrm{MgO}$, see Fig. 1). The common free layer also exhibits an out-of-plane anisotropy and stores the logic information via the magnetic orientation of the free layer. Logic "0" and "1" of the inputs is mapped to the polarity of the input pulses, respectively. A positive current is defined as flowing from one of the inputs towards the free layer (anti-parallel to the z-axis), while the electrons flow in the opposite direction (parallel to the z-axis).

If now one positive current pulse passes through one of the input stacks ($A$ or $B$), the electrons will flow out of the free layer and try to enter the input stack. Since it is easier for electrons with spin parallel to the input stack's orientation to leave the free layer an excess of electrons misaligned to the input stack builds up. They interact with the local free layer's magnetization and excite local precessions. The resulting driving force acts only in the region where the current flows, but through the exchange coupling of the local magnetic moments with their neighbors the precessions start to move out of the polarizer stack overlapping region and travel through the free layer, until they hit the other end, get reflected, move back, get pushed out again and so on [13]. During this kind of oscillating motion, the localized precessions of the magnetic moments in the common free layer are excited and start to build up, until the magnetization eventually passes the energy barrier separating its two stable states and relaxes into the other stable state fast. Applying a second synchronous pulse at the other input stack causes a second spin torque contribution, and the interaction between the two input pulses and their corresponding torques either accelerates (same input polarity) or suppresses (opposing input polarities) the switching of the free layers' magnetization orientation. Therefore, two sufficiently high and long enough pulses with the same polarities either write logic "0" or "1" into the common free layer and two pulses with opposite polarities inhibit each other and the initial magnetization state is held. This behavior perfectly matches the definition of sequential logic whose current output state not only depends on the present inputs but also on former inputs. Inverting one of the inputs even more clearly demonstrates the relation to sequential logic, due to its similarity to RS flip flop logic, but without forbidden input combinations [14].

## III. Simulation

The proposed device has been tested for operational functionality and its sensitivity with respect to device size and input current density variations [11], [15]. In order to keep the new results comparable to the previous findings the same parameters and devices have been employed as in [11] (cf. Tab. I), but instead of varying the input current density, a Zeeman term has been added to take care of the magnetization variations in the free layer (e.g. variations from grain to grain). The device is modeled with the Landau-Lifshitz-Gilbert equation [16], [17]:

| Parameter | Value |
|---|---|
| Free layer thickens $l$ | $3\,\mathrm{nm}$ |
| Contact sizes $a$ | $(10\,\mathrm{nm})^2$, $(20\,\mathrm{nm})^2$, $(30\,\mathrm{nm})^2$ |
| Magnetization saturation $M_S$ | $4\times10^5\,\mathrm{A/m}$ |
| Out-of-plane uni-axial anisotropy $K_1$ | $10^5\,\mathrm{J/m^3}$ |
| Uniform exchange constant $A_{exch}$ | $2\times10^{-11}\,\mathrm{J/m}$ |
| Polarization $P$ | 0.3 |
| Spin barrier | $Cu$ |
| Gilbert gyromagnetic ratio $\gamma$ | $2.211\times10^5\,\mathrm{m/As}$ |
| Damping constant $\alpha$ | 0.01 |
| Non-adiabatic contribution $\epsilon'$ | 0.1[18] |
| $\Lambda$ | 2 |
| Discretization length $\Delta x$,$\Delta y$ | $2\,\mathrm{nm}$ |
| Discretization length $\Delta z$ | $3\,\mathrm{nm}$ |
| Discretization time $\Delta t$ | $2\times10^{-14}s$ |

TABLE I
PARAMETERS USED FOR SIMULATIONS.

$$\frac{\mathrm{d}\vec{\mathrm{m}}}{\mathrm{dt}} = \gamma\left(-\vec{m}\times\vec{H}_{\mathrm{eff}} + \alpha\left(\vec{m}\times\frac{\mathrm{d}\vec{\mathrm{m}}}{\mathrm{dt}}\right) + \vec{T}\right) \quad (1)$$

$\vec{m}$ denotes the reduced magnetization, $\gamma = 2.211\times10^5\,\mathrm{m/As}$ the electron gyromagnetic ratio, $\alpha = 0.01$ the dimensionless damping constant, and $\vec{H}_{\mathrm{eff}}$ the effective field in $\mathrm{A/m}$. The last term in (1) describes the torque acting on the local magnetization due to the polarized electrons. This so called spin transfer torque (STT) $\vec{T}$ is described by the following expression [19]:

$$\vec{T} = \frac{\hbar}{\mu_0 e}\frac{J}{lM_S}\frac{P\Lambda^2}{(\Lambda^2+1)+(\Lambda^2-1)\,\vec{m}\cdot\vec{p}}\cdot \cdot\left(\vec{m}\times\vec{p}\times\vec{m} - \epsilon'\vec{m}\times\vec{p}\right) \quad (2)$$

$\hbar$ denotes the Planck constant, $\mu_0$ the permittivity of vacuum, $e$ the electron charge, $J$ the applied current density, $l$ the free layer thickness, $M_S$ the magnetization saturation, $P$ the polarization, $\vec{p}$ the unit polarization direction of the polarized current, and $\Lambda = 2$ a fitting parameter handling non-idealities. Furthermore, $\vec{H}_{\mathrm{eff}}$ is calculated from the functional derivative of the free energy density containing uni-axial anisotropy, exchange, and demagnetization contributions [20].

As mentioned before an additional Zeeman term is added to the effective field $\vec{H}_{\mathrm{eff}}$. It is assumed that the variations are uncorrelated with respect to position, randomly distributed throughout the free layer, and fixed in time. It is further contemplated that it is more likely to

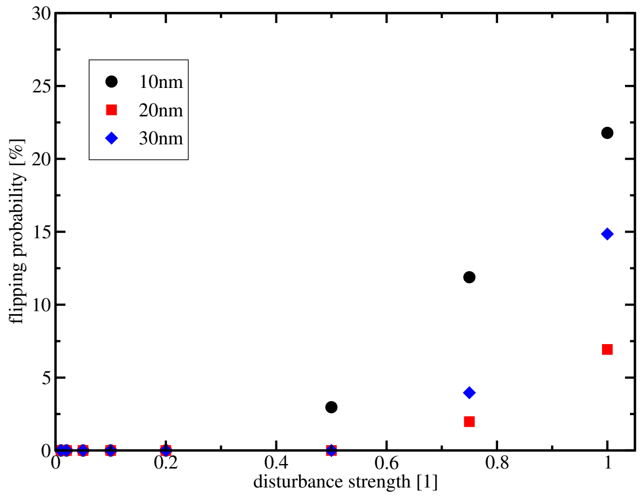


Fig. 2. Simulations to check at which level of added randomization the free layer will flip its orientation without external force.

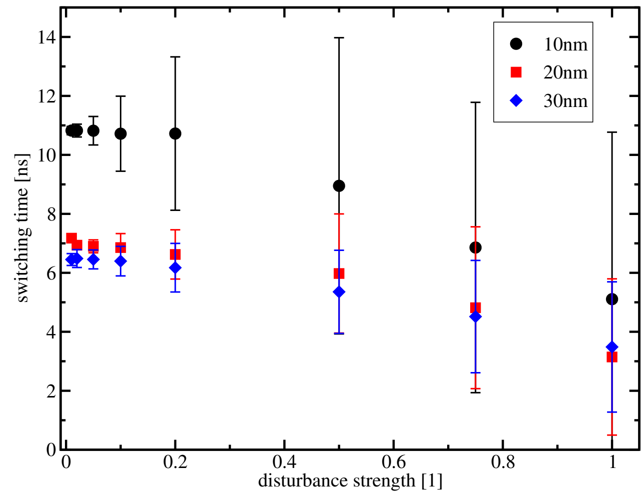


Fig. 3. Switching time as a function of free layer size and disturbance strength.

see small deviations from the out-of-plane magnetization orientation than big differences. Therefore, three Gaussian distributions with random variables $\xi_i$, mean values of $0$ and a variance of $1$ for the x, y, and z-axis are presumed. The random field $H_{i,\mathrm{rand}}$ is defined as function of the random variables $\xi_i$, the free layers magnetization saturation $M_S$, and the relative strength parameter $s$:

$$H_{i,\mathrm{rand}} = \xi_i \, M_S \, s, \quad \mathrm{i} \in \{\mathrm{x}, \mathrm{y}, \mathrm{z}\} \, . \tag{3}$$

For all three simulated layer sizes from [11] ($10\mathrm{nm} \times 40\mathrm{nm} \times 3\mathrm{nm}$, $20\mathrm{nm} \times 80\mathrm{nm} \times 3\mathrm{nm}$, and $30\mathrm{nm} \times 120\mathrm{nm} \times 3\mathrm{nm}$) the parameter $s$ has been set to $0.01$, $0.02$, $0.05$, $0.1$, $0.2$, $0.5$, $0.75$, and $1.0$, respectively. For each $s$ value 101 random free layer samples have been generated and simulated. The input current density for all simulations was set to a value where all three devices are functional $7. \times 10^{10}\mathrm{A/m}^2$ and take around $10\mathrm{ns}$ for switching. The pulse window length was chosen $20\mathrm{ns}$ so the switching events will happen approximately in the middle of the pulse. One input combination for the SET, two for the HOLD operation, and one without any signal for stability checks were calculated.

## IV. Results

As a first step it was checked how the free layer behaves without any current pulse applied. The free layer's magnetization was set parallel to the z-axis plus a small initial deviation from its out-of-plane anisotropy position and then allowed to evolve in time without external forces. Thus, the influence of the random fluctuations on the free layer's ability to hold information in general was tested. The free layer keeps perfectly its initial orientation until $s$ reaches about $50\%$ of the saturation magnetization. At $s = 0.5$ the fluctuations become so strong that more and more of the test structures started to flip (Fig. 2).

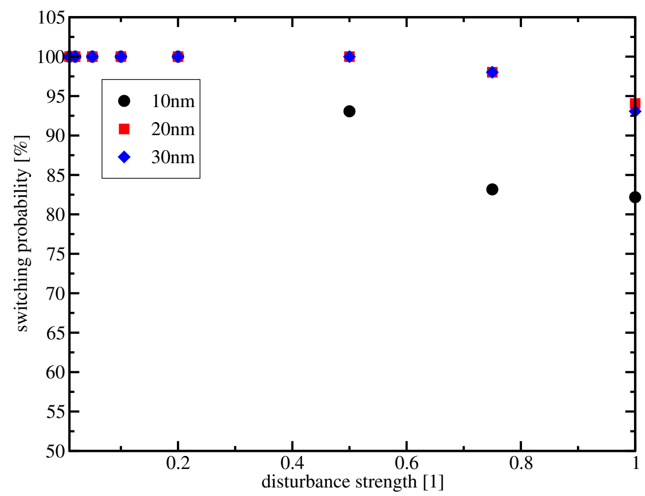


Fig. 4. Switching probabilities for Fig. 3. For 20nm and 30nm the structure switches perfectly until disturbed with 50% of $M_S$ and for 10nm until 20% of $M_S$

Fig. 3 shows the average switching time and the corresponding error bars show $\pm\sigma$ for the SET operation (two synchronous identical pulses) as a function of the free layer's size and relative strength parameter. One can see that for up to $s = 0.2$ there is no significant change in the switching times, but as expected the distribution of switching times broadens with increasing relative strength parameter $s$. Actually, it starts to broaden so much above $s = 0.2$ that the pulse window is not sufficiently long anymore to switch all layers in time. Additionally, as illustrated in Fig. 2, the layer's stability starts to decrease and the downwards position becomes more favorable.

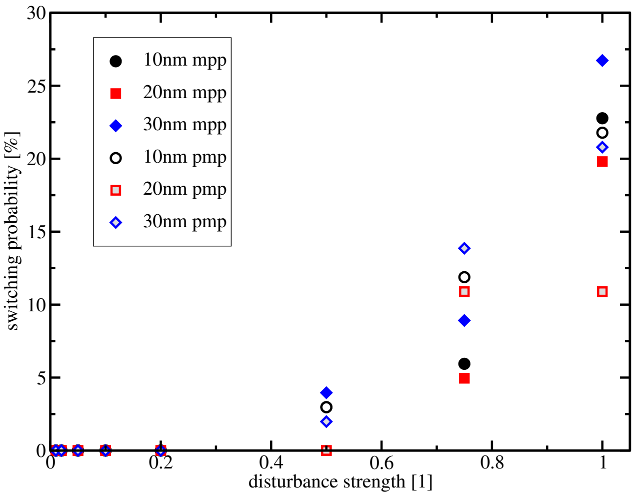


Fig. 5. Switching probabilities as a function of disturbance strength and free layer size. The three letters following the layer width denote the applied input polarities and the initial magnetization orientation of the free layer ($A$, $B$, $Q_0$)

Thus, the calculated switching time average weightings shift to smaller means, since the part of the distribution pointing towards shorter switching times still grows while the part towards longer switching times is cut-off at $20\mathrm{ns}$ in combination with the destabilization of the free layer.

This is also reflected in Fig. 4, where at $s = 0.5$ the switching probability for $10\mathrm{nm}$ layer width starts to drop below $100\%$ and for $20\mathrm{nm}$ and $30\mathrm{nm}$ layer width at $s = 0.75$.

In contrast to the SET operation, the HOLD operation demands that the free layer magnetization does not change, when the two opposing pulses are applied. This again holds true for $s$ between $0.2$ and $0.5$.

## V. Conclusion

Recapitulatory, it could be shown that the presented flip flop device is capable of safely operating even under high free layer inhomogenities. The results were gained under the assumption of space uncorrelated and fixed in time normal distributions. The chosen approach allows easily to test different distribution types and requires only a minimal software adaption. Nevertheless, a big layer magnetization variance leads to broad switching time distributions which might lead to timing problems, e.g. in the worst case the whole circuit will be slowed down by a single device.

## Acknowledgment

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

## References


[1] (2012) International Technology Roadmap for Semiconductors, Chapter PIDS. [Online]. Available: http://www.itrs.net/Links/2012ITRS/Home2012.htm

[2] W. Zhao, L. Torres, Y. Guillemenet, L. V. Cargnini, Y. Lakys, J.-O. Klein, D. Ravelosona, G. Sassatelli, and C. Chappert, "Design of MRAM Based Logic Circuits and its Applications," in *ACM Great Lakes Symposium on VLSI*, 2011, pp. 431–436.

[3] N. Kim, T. Austin, D. Baauw, T. Mudge, K. Flautner, J. Hu, M. Irwin, M. Kandemir, and V. Narayanan, "Leakage Current: Moore's Law Meets Static Power," *Computer*, vol. 36, no. 12, pp. 68–75, 2003.

[4] D. Nikonov and I. Young, "Overview of Beyond-CMOS Devices and a Uniform Methodology for Their Benchmarking," *Proceedings of the IEEE*, vol. 101, no. 12, pp. 2498–2533, 2013.

[5] H. Mahmoudi, T. Windbacher, V. Sverdlov, and S. Selberherr, "Reliability-Based Optimization of Spin-Transfer Torque Magnetic Tunnel Junction Implication Logic Gates," *Advanced Materials Research*, vol. 854, pp. 89–95, 2014.

[6] ——, "Implication Logic Gates Using Spin-Transfer-Torque-Operated Magnetic Tunnel Junctions for Intrinsic Logic-In-Memory," *Solid-State Electronics*, vol. 84, pp. 191–197, 2013.

[7] Everspin Technologies, Jan. 2014. [Online]. Available: http://www.everspin.com/spinTorqueMRAM.php

[8] J. Slaughter, S. Aggarwal, S. Alam, T. Andre, H. J. Chia, M. DeHerrera, S. Deshpande, D. Houssameddine, J. Janesky, F. B. Mancoff, K. Nagel, M. L. Schneider, N. D. Rizzo, and R. Whig, "Properties of CMOS-Integrated Magnetic Tunnel Junction Arrays for Spin-Torque Magnetoresistive Random Access Memory," in *Abstracts of the 58th Annual Conference on Magnetism and Magnetic Materials, Symposium on Materials Advances of Spin-Torque Switched Memory Devices for Silicon Integration*, 2013, pp. BA–01.

[9] D. Worledge, S. L. Brown, W. Chen, J. Harms, G. Hu, R. Kilaru, W. Kula, G. Lauer, L. Q. Liu, J. Nowak, S. Parkin, A. Pushp, S. Murthy, R. P. Robertazzi, G. Sandhu, and J. Sun, "Materials Advances in Perpendicularly Magnetized $mgo$-Tunnel Junctions for STT-MRAM," in *Abstracts of the 58th Annual Conference on Magnetism and Magnetic Materials, Symposium on Materials Advances of Spin-Torque Switched Memory Devices for Silicon Integration*, 2013, pp. BA–02.

[10] L. Thomas, G. Jan, J. Zhu, H. Liu, Y. Lee, S. Le, R. Tong, K. Pi, Y.Wang, T. Zhong, T. Torng, and P.Wang, "Magnetization Dynamics in Perpendicular STT-MRAM Cells with High Spin-Torque Efficiency and Thermal Stability," in *Abstracts of the 58th Annual Conference on Magnetism and Magnetic Materials, Symposium on Materials Advances of Spin-Torque Switched Memory Devices for Silicon Integration*, 2013, pp. BA–03.

[11] T. Windbacher, H. Mahmoudi, V. Sverdlov, and S. Selberherr, "Rigorous Simulation Study of a Novel Non-Volatile Magnetic Flip Flop," in *Proc. of the SISPAD*, 2013, pp. 368–371.

[12] ——, "Spin Torque Magnetic Integrated Circuit," EU Patent EP13 161 375, Mar. 27, 2013.

[13] R. Hertel, *Handbook of Magnetism and Advanced Magnetic Materials*. John Wiley & Sons, Ltd, 2007, ch. Guided Spin Waves.

[14] U. Tietze and C. Schenk, *Electronic Circuits – Handbook for Design and Applications*, 2nd ed. Springer, 2008, no. 12.

[15] M. Donahue and D. Porter, "OOMMF User's Guide," National Institute of Standards and Technology, Gaithersburg, MD, Interagency Report NISTIR 6376, Sept 1999, version 1.0.

[16] T. Gilbert, "A Lagrangian Formulation of the Gyromagnetic Equation of the Magnetization Field." *Phys. Rev.*, vol. 100, p. 1243, 1955.

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

[18] A. V. Khvalkovskiy, K. A. Zvezdin, Y. V. Gorbunov, V. Cros, J. Grollier, A. Fert, and A. K. Zvezdin, "High Domain Wall Velocities Due to Spin Currents Perpendicular to the Plane," *Phys. Rev. Lett.*, vol. 102, p. 067206, Feb 2009.

[19] J. Xiao, A. Zangwill, and M. D. Stiles, "Boltzmann Test of Slonczewski's Theory of Spin-Transfer Torque," *Phys. Rev. B*, vol. 70, p. 172405, Nov 2004.

[20] J. E. Miltat and M. J. Donahue, *Handbook of Magnetism and Advanced Magnetic Materials*. John Wiley & Sons, Ltd, 2007, ch. Numerical Micromagnetics: Finite Difference Methods.