ECS Transactions, 97 (5) 159-164 (2020)
10.1149/09705.0159ecst ©The Electrochemical Society

Influence of Current Redistribution in Switching Models for Perpendicular STT-MRAM

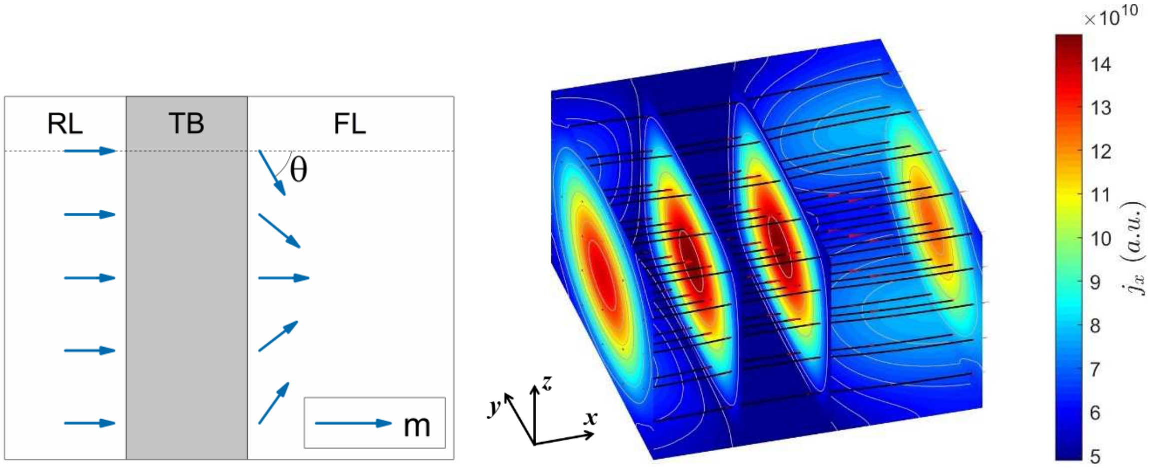
S. Fiorentini[1], R.L. de Orio[1,2], S. Selberherr[2], J. Ender[1], W. Goes[3], and V. Sverdlov[1]

[1]Christian Doppler Laboratory for NOVOMEMLOG at the
[2]Institute for Microelectronics, TU Wien, Gußhausstraße 27-20, 1040 Vienna, Austria
[3]Silvaco Europe Ltd., Cambridge, United Kingdom
e-mail: fiorentini@iue.tuwien.ac.at; phone: +43 15880136001

Simulation of switching in spin-transfer torque magnetoresistive random access memory is usually performed by assuming that the torque is created by a position- and time-independent current density. However, in real circuits the voltage is fixed, not the current density. The assumption of a fixed current density, especially in modern devices with a tunneling magnetoresistance up to 200%, becomes thus questionable. In this work we compare the switching time distribution obtained under the assumptions of fixed voltage and fixed current density for a wide range of tunneling magnetoresistance and surface area values. We demonstrate that the approximate fixed current density approach can reproduce the correct switching times, provided that the current value is appropriately adjusted. We show that the correction on the current depends on the switching speed, dictated by different system parameters.

Introduction

The outstanding improvement in the performance of modern integrated circuits is supported by the continuous down-scaling of semiconductor devices. However, this leads to a substantial increase in leakages, which results in growing stand-by power consumption. A viable path to mitigate these issues is the introduction of non-volatility in integrated circuits. Spin-transfer torque (STT) magnetoresistive random access memory (MRAM) is a promising candidate (1-6). It is competitive with conventional non-volatile flash memory as it combines high speed, excellent endurance, and low costs. The range of potential STT-MRAM utilization goes from automotive and Internet-of-Things applications to embedded memories and last level caches (7). The core of an STT-MRAM device is a magnetic tunnel junction (MTJ), where the relative orientation of its magnetic layers provides a way of storing binary information. Switching between the two possible configurations is achieved by passing an electric current through the structure (8,9). The electrons become spin-polarized by the reference layer (RL) and, when entering the free layer (FL), act via the exchange interaction on its magnetization by exerting a torque. With a sufficiently large current density, the magnetization of the free layer can be flipped. The usual approach for micromagnetic simulations of STT switching is to assume a constant and uniform current density (10). In circuits and applications, however, the voltage, rather than the current density, is fixed during the switching process. As the tunneling resistance in an MTJ depends on the changing relative magnetization orientation of the two magnetic layers, the current depends on time. Moreover, the magnetization of the free layer is non-uniform



(a) (b)

Figure 1. (a) Schematization of an MTJ structure with non-uniform free layer (FL) magnetization. TB is the tunnel barrier and RL the reference layer. (b) Non-uniform distribution of the current density in the MTJ. The current flows towards the paths of minimum resistivity, where the magnetization vectors in the two layers are aligned.

during switching, which results in a position- (and time-) dependent current density $\mathbf{J}(\mathbf{r}, t)$ (Fig. 1). The assumption of a constant and uniform current density is thus violated, especially in devices with tunneling magnetoresistance ratios (TMR) of about 200% and higher (11). In order to clarify, if the fixed current density assumption for switching time evaluation can be still used, we compare its results with switching at a fixed voltage. We also consider a description in which the total current is fixed, but the current density is locally determined by the magnetization alignment and the corresponding TMR value.

STT-MRAM Model

In modern MRAM cells the binary information is stored as the relative orientation of the magnetic layers in an MTJ, which consists of a sandwich of two ferromagnetic layers and an insulating tunneling layer. The magnetization in the free layer (FL) can switch, while the magnetization in the second, reference layer (RL) is fixed by the exchange coupling to a pinned layer (12). CoFeB is typically used for the magnetic layers, while MgO is the typical material for the insulating layer, as it provides a good TMR. The TMR is defined as

$$TMR = \frac{G_P - G_{AP}}{G_{AP}}, \qquad [1]$$

where G_P and G_{AP} are the conductances in the parallel and anti-parallel states, respectively. Another beneficial property of this choice of materials is the interface coupling between MgO and CoFeB, which renders the ferromagnetic layers perpendicularly magnetized. In this configuration, the thermal relaxation path and the switching path coincide, leading to lower switching currents as compared to structures with in-plane magnetization. The development of tools which are able to properly simulate the switching process and the torques acting on the magnetization can improve the design of novel MRAM devices. The magnetization dynamics is described by the Landau-Lifshitz-Gilbert (LLG) equation. With a spin transfer torque term added, the LLG equation for the free layer reads as (13)

$$\frac{\partial \mathbf{m}}{\partial t} = -\gamma\mu_0 \mathbf{m}\times\mathbf{H}_{\text{eff}} + \alpha\mathbf{m}\times\frac{\partial \mathbf{m}}{\partial t} + \frac{1}{M_S}\mathbf{T_S} \quad [2a]$$

$$\mathbf{T_S} = \gamma\frac{\hbar}{2e}\frac{0.5\, J_C\, P}{d\left(1+P^2\cos\theta\right)}\mathbf{m}\times(\mathbf{m}\times\mathbf{x}), \quad [2b]$$

where γ is the gyromagnetic ratio, μ_0 is the vacuum permeability, $\mathbf{m}=\mathbf{M}/M_S$ is the position-dependent normalized magnetization in the free layer, M_S is the saturation magnetization in the free layer, α is the Gilbert damping factor, $\hbar$ is the reduced Plank constant, e is the electron charge, J_C is the magnitude of the current density, P is the spin current polarizing factor (13), which is assumed equal in the two magnetic layers for this work, d is the thickness of the free layer, θ is the angle between local magnetization vectors in the free and reference layers, $\mathbf{x}$ is the direction of the magnetization in the reference layer, and $\mathbf{H_{eff}}$ is the effective magnetic field, containing different contributions, namely the external field, the exchange interaction, the anisotropy field, the Ampere field, the demagnetizing field, and the stray field from the reference layer. In order to simulate the switching at a finite temperature, a stochastic thermal contribution to $\mathbf{H_{eff}}$ is also included.

The usual approach for STT-switching simulations is to assume a constant and uniform value for J_C. In order to test this assumption in an MTJ with TMR=200% and non-uniform magnetization in the free layer, we compute the current density flowing through the structure as

$$\mathbf{J}_C = -\sigma\nabla V, \quad [3]$$

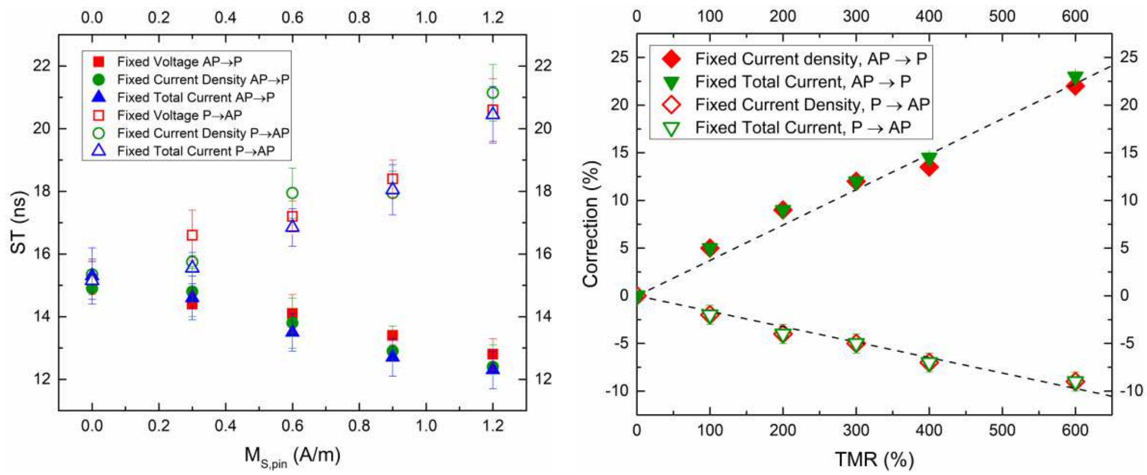
where V is the electric potential and σ is the conductivity. The potential in the ferromagnetic leads is computed by solving the Laplace equation $\nabla^2 V = 0$. The local conductance of the barrier, taken as suggested in (14) as

$$G(\theta) = \frac{G_P + G_{AP}}{2}\left(1+\left(\frac{TMR}{2+TMR}\right)\cos\theta\right), \quad [4]$$

is imposed as a boundary condition on the ferromagnet/insulator interface. In Fig. 1b the results for the configuration schematized in Fig. 1a are shown. As a result of the non-uniform conductance of the structure, the current density is highly non-uniform too. Thus, it is necessary to evaluate the impact of assuming a fixed voltage on the simulation of magnetization reversal.

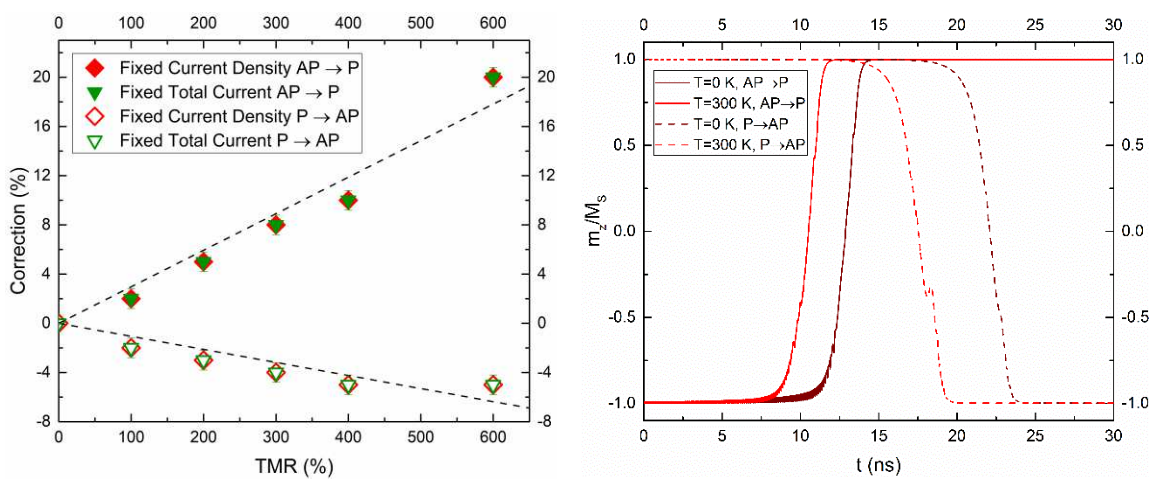
Results

We compare a realistic approach in which the *voltage* during switching is kept constant with the *fixed current density* approach. In addition, the fixed voltage and fixed current density models are compared to an approach (15), generalized to p-MTJs, in which the *total current* is fixed, but redistributed according to the position-dependent resistance determined by the local relative magnetization orientation in the two magnetic layers. Herein, the value of the current in the fixed current/current density models is equal to the voltage in the fixed voltage model divided by the resistance in the *initially* parallel (P) or anti-parallel (AP) state. The free layer is perpendicularly magnetized. The switching time depends on the realization of the stochastic magnetic field, which mimics the magnetization fluctuations at room temperature. It is demonstrated that, by slightly increasing the current



(a) (b)

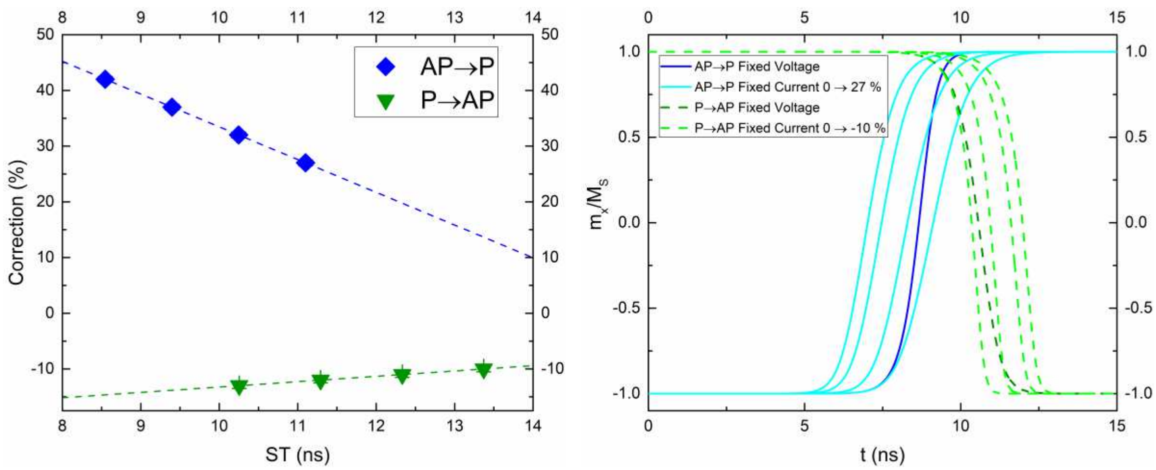
Figure 2. (a) Switching times (ST) for the three approaches as a function of the stray field from the reference layer, modeled by its saturation magnetization (M_S), after applying the current correction. Error bars represent the thermal distribution. (b) Dependence of the current correction on the TMR for both P→AP and AP→P switching, for T=300 K. The dashed lines represent a linear fit.



(a) (b)

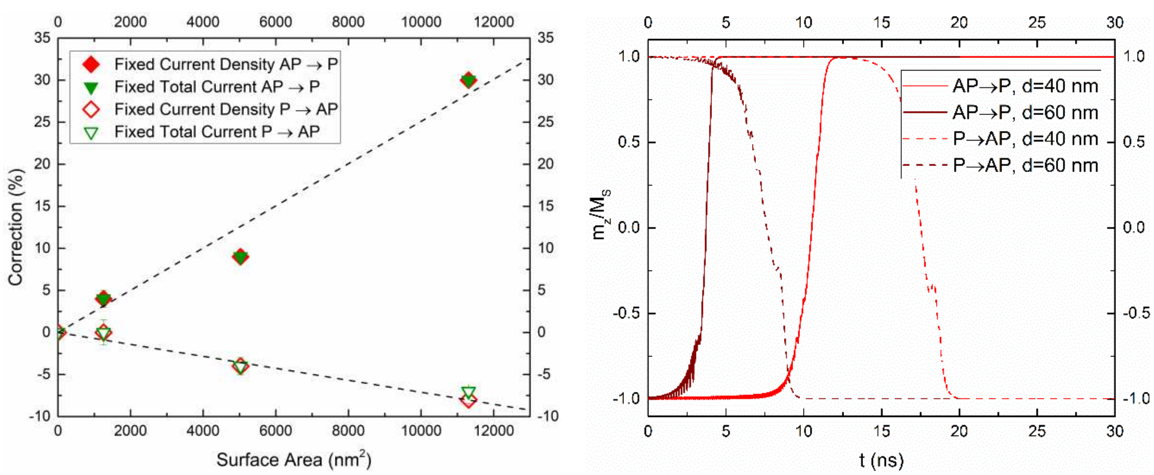
Figure 3. (a) Dependence of the current correction on the TMR for both P→AP and AP →P switching, for T=0 K. (b) Comparison between switching realizations for the fixed voltage approach at T=0 K and T=300K.

from its initial value for AP to P switching and decreasing it for P to AP switching, the switching time distributions can be matched (16) for any value of the stray field induced by the reference layer (Fig. 2a). Here, we systematically study the dependence of this current correction on system parameters. The dependence of the current correction on the TMR at room temperature is reported in Fig. 2b. It is observed that the value of the correction increases with higher TMR. We then performed simulations at zero temperature, and in this case, the required correction to reproduce the fixed voltage results is lower than the one at room temperature, while it still increases with the TMR (Fig. 3a). However, the switching time at zero temperature is also longer than at room temperature, as shown in Fig. 3b. This provides a strong indication that the correction to the current is not universal and depends on the system parameters. To elaborate on the physical origin of this dependence we performed macrospin simulations with the free layer represented by a single cell. The initial magnetization direction is slightly tilted from its perfect perpendicular orientation in order to reduce the incubation time of switching. By gradually increasing the tilting angle, one can monitor the dependence of the current correction on the switching time, as reported in Fig. 4a. The data show that a faster switching requires a higher correction to the current value, which explains the difference between the room and zero temperature simulations. As the switching is faster at room temperature, the correction required on the current is also higher. The macrospin results can also help to explain the origin of the current correction. Fig. 4b reports switching realizations for the fixed voltage and the fixed current density models with increasing values of the correction. The



(a) (b)

Figure 4. Macrospin simulations to explain the origin and behavior of the current correction. In (a) the dependence of the current correction on the switching time is reported. Shorter switching times require a larger current correction. In (b) we show how the correction affects the switching realization, for both AP→P and P→AP. The different slope of the fixed current approach is compensated by the current correction.



(a) (b)

Figure 5. (a) Dependence of the current correction on the surface area of the structure at T=300 K, for both P→AP and AP→P switching. The dashed lines represent a linear fit. (b) Comparison between switching realization for the fixed voltage approach with a structure diameter of d=40 nm and d=60 nm.

correction is necessary for the switching process in the fixed current density approach to begin earlier for AP→P and later for P→AP, in order to compensate the difference in the slope to the fixed voltage approach. As an additional test of the dependence of the correction on system parameters, we performed simulations for different values of the surface area of the structure at room temperature. The results are reported in Fig. 5. The required current correction increases with the surface area (Fig. 5a). This implies that the switching in a structure with a larger diameter is faster, and this is indeed observed in Fig. 5b in agreement with the macrospin results.

Conclusion

We performed simulations of switching in an STT-MRAM structure. We compared the switching time distribution obtained under the assumption of a fixed voltage during switching to the ones obtained under the approximation of fixed current density and fixed total current across the structure. We showed that it is possible to reproduce the switching times obtained within the realistic fixed voltage approach with the approximate fixed current density approach for a wide range of system parameters, provided that the dependence of the current correction on such parameters is taken into consideration.

Acknowledgments

This work was supported by the Austrian Federal Ministry for Digital and Economic Affairs and the National Foundation for Research, Technology and Development.

References

1. S.Aggarwal, H.Almasi, M.DeHerrera *et al*., *Proceedings of the IEDM*, 2.1.1 (2019).
2. K.Lee, J.H.Bak, Y.J.Kim *et al*., *Proceedings of the IEDM*, 2.2.1 (2019).
3. V.B.Naik, K.Lee, K.Yamane *et al*., *Proceedings of the IEDM*, 2.3.1 (2019).
4. J.G.Alzate, U.Arslan, P.Bai *et al*., *Proceedings of the IEDM*, 2.4.1 (2019).
5. G.Hu, J.J.Nowak, M.G.Gottwald *et al*., *Proceedings of the IEDM*, 2.6.1 (2019).
6. W.J.Gallagher, E.Chien, T.W.Chiang *et al*., *Proceedings of the IEDM*, 2.7.1 (2019).
7. S.Sakhare, M.Perumkunnil, T.H.Bao *et al*., *Proceedings of the IEDM*, 420 (2018).
8. J.C.Slonczewski, *Journal of Magnetization and Magnetic Materials* **159**, L1 (1996).
9. L.Berger, *Physical Review B* **54**, 9353 (1996).
10. A.Makarov, T.Windbacher, V.Sverdlov, and S.Selberherr, *Semiconductor Science and Technology* **31**, 113006 (2016).
11. W.Skowronski, M.Czapkiewicz, S.Zietek, *et al.*, Scientific Reports **7**, 10172 (2017).
12. S.Bhatti, R.Sbiaa, A.Hirohata, *et al*., *Materials Today* **20**, 530 (2017).
13. A.Makarov, *Ph.D. Thesis*, Institute for Microelectronics, TU Wien, Vienna (2014).
14. J.Slonczewski, *Physical Review B* **71**, 024411 (2005).
15. D.Aurelio, L.Torres, and G.Finocchio, *Journal of Magnetization and Magnetic Materials* **321**, 3913 (2009).
16. S.Fiorentini, R.Orio, W.Goes *et al.*, *Proceedings of the SISPAD*, 57 (2019).