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Micromagnetic model for studies on Magnetic Tunnel Junction switching dynamics, including local current density

Marek Frankowski*, Maciej Czapkiewicz, Witold Skowroński, Tomasz Stobiecki

Department of Electronics, AGH University of Science and Technology, al. Mickiewicza 30, 30-059 Kraków, Poland

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ABSTRACT

We present a model introducing the Landau–Lifshitz–Gilbert equation with a Slonczewski's Spin-Transfer-Torque (STT) component in order to take into account spin polarized current influence on the magnetization dynamics, which was developed as an Object Oriented MicroMagnetic Framework extension. We implement the following computations: magnetoresistance of vertical channels is calculated from the local spin arrangement, local current density is used to calculate the in-plane and perpendicular STT components as well as the Oersted field, which is caused by the vertical current flow. The model allows for an analysis of all listed components separately, therefore, the contribution of each physical phenomenon in dynamic behavior of Magnetic Tunnel Junction (MTJ) magnetization is discussed. The simulated switching voltage is compared with the experimental data measured in MTJ nanopillars.

1. Introduction

Magnetic Tunnel Junction (MTJ), consisting of two ferromagnetic nano-layers separated by a thin insulating barrier, has recently drawn a significant attention, due to their potential applications such as Spin-Transfer-Torque Random Access Memory (STT-RAM) [1], magnetic field sensors [2] and microwave oscillators [3]. The major advantage of MTJs is the possibility of the magnetization control of one of the ferromagnetic layers – called the Free Layer (FL) with a spin polarized current by means of the STT effect [4,5]. Due to the STT, the applied spin polarized current can drive the magnetization of the FL into precession, laying typically in a microwave frequency regime [6] or, for sufficiently high current amplitudes, it can switch the FL between Parallel (P) and Anti-Parallel (AP) alignment with respect to the Reference Layer (RL) [7,8]. The difference between the P and AP states can be detected using the Tunnel Magnetoresistance (TMR) effect [9].

In order to fully understand the magnetization switching process, micromagnetic simulations are commonly used, in order to derive the parameters not-accessible in the experiment, or to support the optimization of the MTJ design. In this paper we present a model which was adopted to an extension of Object Oriented MicroMagnetic Framework (OOMMF) [15] that allows for accurate local current density calculation, which is crucial for the magnetization switching dynamics. We implement the feedback between the local magnetizations alignment, the current density and the conductivity. Recent publications used macrospin models [11,10], or focused on the simulations with a fixed current density or a current pulse independent of the dynamic MTJ resistance [12–14].

2. Implemented models

In our MTJs model we assume that the current flows through channels perpendicular to the junction plane, which are connected in parallel. Each channel is considered as separate junction with the resistance R, which depends on the TMR effect given by the formula:

$$R = R_P + \frac{R_{AP} - R_P}{2}(1 - \cos\,\theta), \quad (1)$$

where θ is an angle between magnetization vectors of FL and RL, R_P (for $\theta = 0$) and R_{AP} (for $\theta = 180^\circ$) are resistances of the P and AP states, respectively. The idea of calculating local conductance is depicted in Fig. 1(a). The detailed specification of the OOMMF settings files as well as the used source code can be found on one of the authors home page [16].

In addition to the local conductance channels, the Oersted field caused by the current flow was integrated in our model. The Oersted field calculations are performed by adding the contributions from current channels extended beyond the simulation space. This method is justified because the non-ferromagnetic parts of the real device, i.e., the buffer and capping layers, are usually much thicker than the simulated ferromagnetic MTJ trilayer. Assuming that current channel protrudes symmetrically from simulated area, Oersted field contributions are calculated

* Corresponding author. Tel.: +48 126174474.
E-mail address: mfrankow@agh.edu.pl (M. Frankowski).

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using the formula: $H=(I/2\pi r)d/\sqrt{r^2+d^2}$, where I is the current in the channel, r is the distance between the channel and the considered simulation cell, d is half of the total channel length (see Fig. 1(b)). After adding contributions from all channels, the Oersted field can be treated as the contribution to the effective magnetic field in a particular cell.

For a simulation of the magnetization dynamics, we use the Landau–Lifshitz–Gilbert equation with the STT component:

$$\frac{d\vec{m}}{dt}=-\gamma_0\vec{m}\times\vec{H}_{eff}+\alpha\vec{m}\times\frac{\partial\vec{m}}{\partial t}+\gamma_0 a_J\vec{m}\times(\vec{m}\times\vec{p})+\gamma_0 b_J\vec{m}\times\vec{p}. \quad (2)$$

First term of Eq. (2) corresponds to the magnetization precession, second corresponds to damping, third and fourth correspond to in-plane and perpendicular torques, respectively, where $\vec{m}$ is the normalized magnetization vector of the FL, $\gamma_0=2.21\times10^5$ m/As is the gyromagnetic factor, $\vec{H}_{eff}$ is the effective field derived by minimizing the local energy densities, α is the damping factor, and $\vec{p}$ is the normalized RL magnetization vector. The in-plane torque factor is written as follows: $a_J=(\hbar/2e\mu_0 M_s t)\varepsilon J$, where t is the FL thickness, ε=0.7 is the STT coefficient, J is the current density, whereas the perpendicular torque is implemented as follows: $b_J=b_1J+b_2J^2$, where $b_1=2.7\times10^{-9}$ m and $b_2=2.8\times10^{-19}$ m^3/A are the quadratic function components, taken from the experimental data [3].

Our model allows one to adjust the following parameters: η, b_1, b_2, α, R_P, R_{AP}, while the applied time dependent voltage is the stimulus vector. By setting η or b_1 and b_2 to zero, the contribution from the in-plane torque or the perpendicular torque can be ignored, respectively. In addition, the model enables performing the micromagnetic simulations with the current density that depends on the local magnetization vectors alignment.

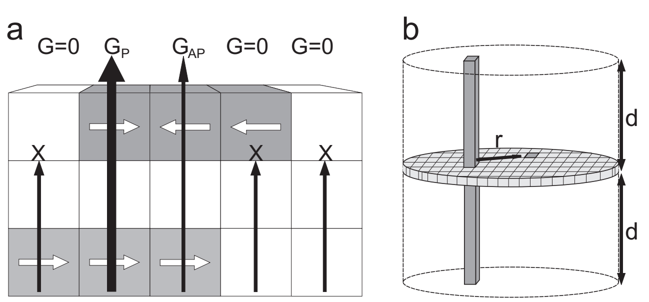

Fig. 1. (a) The idea of calculating local conductance. White cells represent the non-ferromagnetic material and gray cells represent the ferromagnetic material with its magnetization vector. Vertical arrows symbolize the current, whereas crosses stay for channels with the suppressed current. (b) The illustration to the Oersted field calculation. The contribution from the channel of length 2d is added to the cell located in the distance r from that channel.

3. Results and discussion

In order to compare simulation results to the experimental values obtained from real devices, we investigated exchange biased MTJ with a following multilayer structure (thickness in nm): Ta(5)/CuN(50)/Ta(3)/CuN(50)/Ta(3)/PtMn(16)/$Co_{70}Fe_{30}$(2)/Ru (0.9)/$Co_{20}Fe_{40}B_{20}$(2.3)/MgO(0.95)/$Co_{20}Fe_{40}B_{20}$(2.3)/Ta(10)/CuN (30)/Ru(7), described in detail in Ref. [3]. Nano-structured pillars with an elliptical cross-section of 250 × 150 nm were parametrized for our model purposes in the following way: cell size of 2 × 2 × 1 nm, FL with the anisotropy constant of $K_{FL}=0.1$ kJ/m^3, saturation magnetization of $M_{FL}=$ 1100 kA/m and the damping constant equals $\alpha=0.017$, coupled to the RL with the coupling energy of $J_{MgO}=0.006$ mJ/m^3. The RL was antiferromagnetically coupled to the CoFe pinned layer with the energy of $J_{Ru}=-0.019$ mJ/m^3.

The implemented feedback between the local current density and the magnetization involves dynamic decrease in the MTJ resistance. Therefore, for applied bias voltage, the current increases with the conductivity and the switching process can be accomplished faster. Fig. 2 presents the dynamic behavior of the MTJ normalized magnetization vector during the switching process from the AP to P state with the fixed current (a) and the current-resistance feedback (b). The difference confirms that this feedback has an influence on switching dynamics and should be taken into account in the simulations.

Simulated Current Induced Magnetization Switching (CIMS) loops, with (a) in-plane torque component alone, (b) both in-plane and perpendicular torque components, and (c) both torque components and Oersted field, are presented in Fig. 3(a–c). In addition, Fig. 3(d–f) depicts the MTJ resistance during the voltage sweep as a function of time. Note that for the Oersted field applied (Fig. 3(f)) the CIMS switching is accomplished for the shortest time. Moreover, for sufficiently high voltage amplitude, the perpendicular torque can overcome the in-plane torque and can cause indeterministic switching between the AP and P states. This phenomenon has been already observed experimentally and has been referred to as the back-hopping effect [17].

The discussed MTJ experimental CIMS loop is depicted in Fig. 4 (a) – resistance measured after voltage pulse and (b) – during the pulse. In our simulations we are interested in the switching of the MTJ, so we assume that the resistance of AP state equals value at the switching voltage obtained by the experiment in Fig. 4(b).

The simulated switching voltage from the AP to P state agrees quantitatively with the experimental value of V_s=0.75 V, in contrary to the opposite switching polarity, where the discrepancy between simulated and measured values is observed. Such an asymmetry in the simulated switching voltages presented in Fig. 3 (c) originates from the Oersted field effect, that favors the AP to P

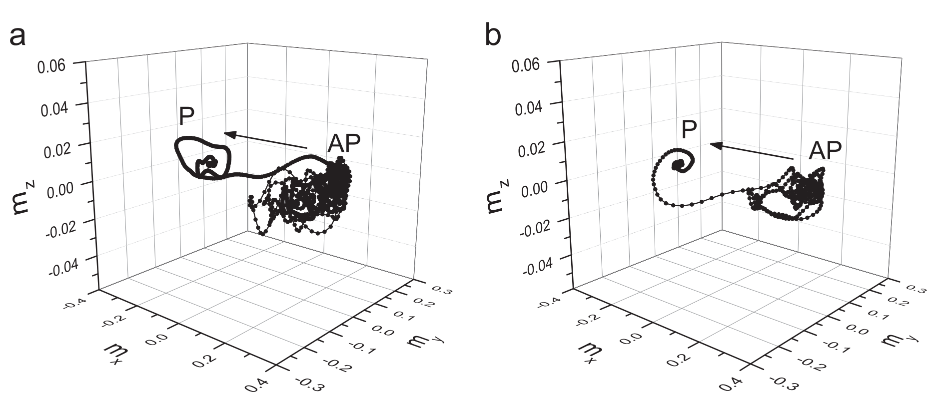

Fig. 2. Trajectories of normalized magnetization vector of the system during switching from the AP to P state in case of: (a) fixed current density, (b) changing local current density due to the resistance-current feedback. Arrows show the direction of magnetization switching.