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

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Abstract

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 nonvolatility in integrated circuits. Spin-transfer torque (STT) magnetoresistive random access memory (MRAM) is a promising candidate. It is competitive with conventional nonvolatile flash memory as it combines high-speed, excellent endurance, and low costs. The range of potential STT-MRAM applications goes from automotive and Internet-of-Things to embedded memories on System-on-Chips and L3 caches [1]. The core of an STT-MRAM device is a magnetic tunnel junction, where the relative orientation of its magnetic layers provides a way of storing the binary information. Switching between the two possible configurations is achieved by passing an electric current through the structure. The electrons get spin-polarized by the reference layer and, when entering the free layer, act via the exchange interaction on its magnetization providing the 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 [2]. 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 relative magnetization orientation of the two layers, the current depends on time. Moreover, the magnetization of the free layer is nonuniform during switching, which results in a position (and time) dependent current density $\mathbf{J}(\mathbf{r},t)$ (Fig. 1). In order to evaluate the validity and the limits of the fixed current density approach in computing the switching time, we compare it with a model in which the total current is fixed, but redistributed according to the position-dependent resistance [3], determined by the local magnetization orientation. In addition, the fixed current and the fixed current density models are compared with a realistic approach in which the

voltage during switching is kept constant. 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 *initial* 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 from its initial value for AP to P switching and decreasing it for P to AP switching, the switching time distributions can be matched [4] for any value of the stray field induced by the pinned layer (Fig.2). Here, we systematically study the dependence of this current correction on system parameters. The dependence of the current correction on the tunneling magnetoresistance ratio (TMR) at room temperature is reported in Fig. 3. 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 correction required to reproduce the fixed voltage results is lower than the one at room temperature (Fig. 4). However, the switching is also slower. This proves 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. The initial magnetization orientation is slightly tilted from its perfect perpendicular orientation in order to reduce the incubation time of switching. By changing the initial tilting of the magnetization, we demonstrate that a faster switching requires a higher correction to the current value, which explains the difference between the room and zero temperature simulations (Fig. 5). Simulation results for the current correction as a function of the surface area of the structure at room temperature are shown in Fig. 6. The switching is faster for higher values of the area, and the current correction required is consequently higher, in agreement with the macrospin results. We conclude 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.

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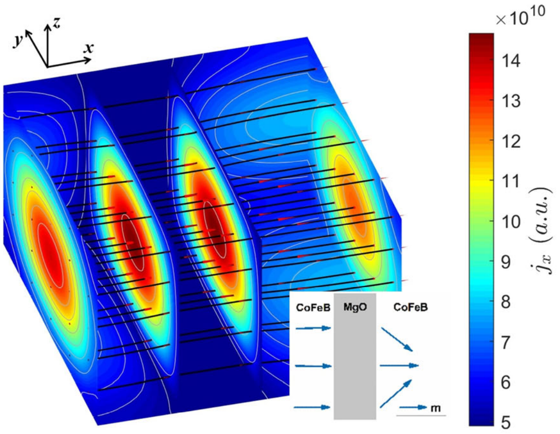

Fig. 1. Current density computed in the structure reported in the inset: the current is redistributed in order to accommodate the nonuniform resistance coming from the nonuniform magnetization in the free layer.

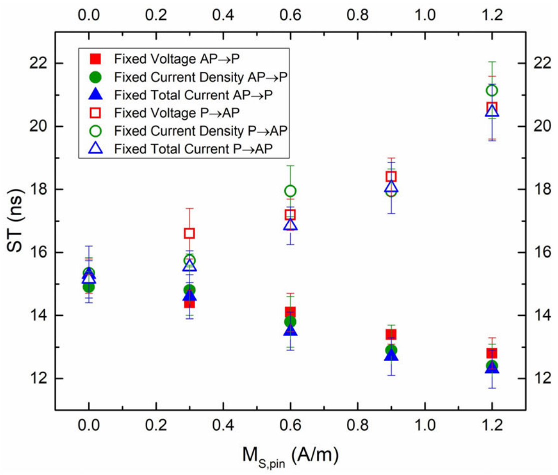

Fig. 2. Switching times (ST) for the three approaches as a function of the stray field from the pinned layer, modeled by its saturation magnetization (M_S), after applying the current correction. Error bars represent the thermal distribution.

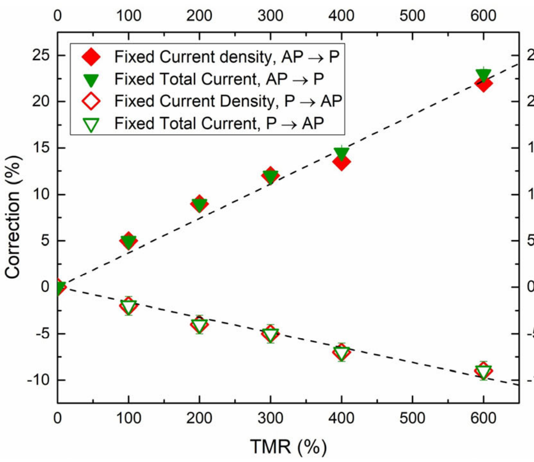

Fig. 3. Dependance of the current correction, which must be given for all the models to produce consistent results, on the TMR at T=300 K, for both P→AP and AP→P switching. The dashed lines represent a linear fit.

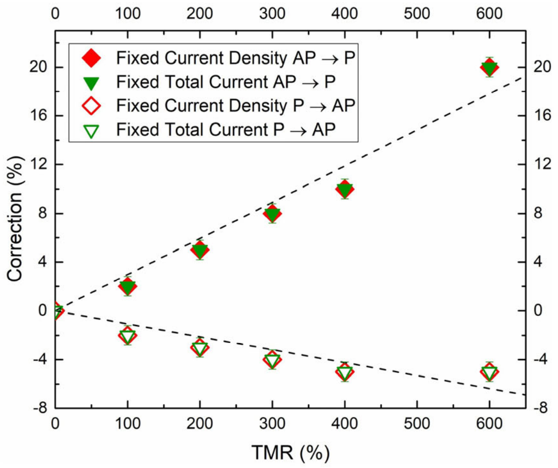

Fig. 4. Dependance of the current correction on the TMR, for T=0 K and both P→AP and AP→P switching. The dashed lines represent a linear fit.

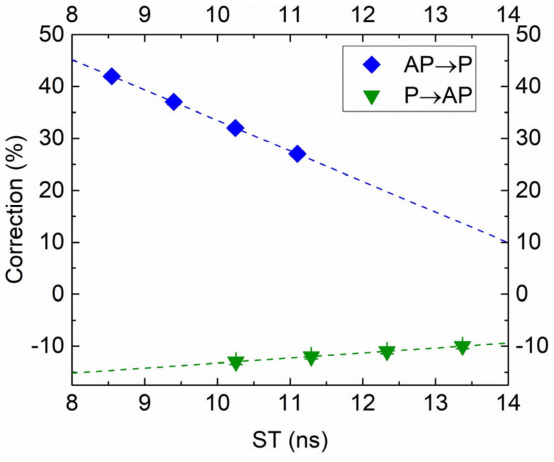

Fig. 5. Dependence of the current correction on the switching time in a macrospin scenario, for T=0 K and both P→AP and AP→P switching. The dashed lines represent a linear fit.

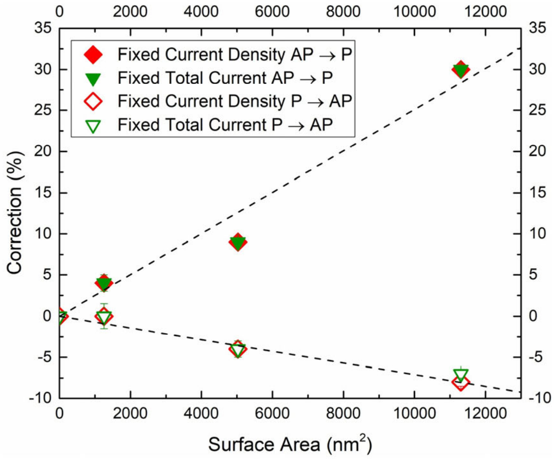

Fig. 6. Dependence of the current correction on the surface area of the structure at T=300 K, for both P→AP and AP→P switching. The dashed lines represent a linear fit.