

Perpendicular STT-MRAM Switching at Fixed Voltage and at Fixed Current

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Abstract—The magnetization dynamics of a free layer in spin-transfer torque MRAM is usually determined by the torque created by a position-independent current density. In circuits, the voltage, not current density, is fixed during switching. Therefore, the approximate evaluation of the torque based on the fixed current density becomes questionable in modern magnetic tunnel junctions with a tunneling magnetoresistance ratio of about 200%, where the current densities across the structure can vary by a factor of three. We compare the switching times obtained within a fixed voltage assumption with those from the approximate fixed current density approach. We demonstrate that the fixed current approach can reproduce the correct switching also in the case of high TMR, if the current is appropriately adjusted. It is shown that the correction to the current is not universal and depends on the temperature and the switching speed.

Keywords—spin-transfer torque, MRAM, perpendicular magnetization, tunneling magnetoresistance

I. INTRODUCTION

The present progress in development of computer memory is supported by scaling of semiconductor components. This, however, results in increased power consumption at stand-by due to leakages. The introduction of non-volatility in modern integrated circuits can dramatically reduce the stand-by power and the leakages. Spin-transfer torque (STT) magnetoresistive random access memory (MRAM) combines high speed, excellent endurance, and low costs and is promising for applications ranging from IoT and automotive applications to embedded DRAM and L3 caches [1].

In MRAM the binary information is stored as the relative orientation of the magnetic layers in a magnetic tunnel junction (MTJ). The switching between the orientations is achieved by the spin-polarized current due to the electrical

current passing through the MTJ. When the magnetization in the layers is not aligned, the spin polarization of the electrons polarized in the fixed reference layer aligns almost immediately with the magnetization in the free layer. As the total spin angular momentum in the free layer is conserved, the spin current polarization change is transferred to the magnetization via the exchange interaction. This is equivalent to the spin-transfer torque acting on the magnetization of the free layer as the electrical current flows through the magnetic tunnel structure [2], [3]. If the current is sufficiently strong, the magnetization of the free layer can be switched between the two stable configurations, parallel (P) or anti-parallel (AP), relative to the reference layer.

In micromagnetic modeling of STT switching, it is usually assumed that the current density $\mathbf{J}(\mathbf{r},t)$ is position- and time-independent [4]. In circuits, however, the voltage rather than the current density remains fixed during switching. Because the resistance of the tunnel junction depends on the relative magnetization alignment in the free and the reference layer, the current through the structure is not constant during the switching. Even more, as the relative magnetization alignment at switching is not uniform along the free layer and depends on the position, so does the local tunneling conductance. Therefore, different current densities are flowing through different parts of the MTJ with a position-dependent magnetization alignment (Fig.1, inset). The assumption of a constant current density adopted in the description of STT-MRAM switching is violated, especially in advanced MTJs with a tunneling magnetoresistance ratio (TMR) of about 200% and higher [5].

In order to define the validity of the description with the fixed current density for evaluating the switching time, we also consider an approach in which the total current is fixed, but the current density is determined by the local

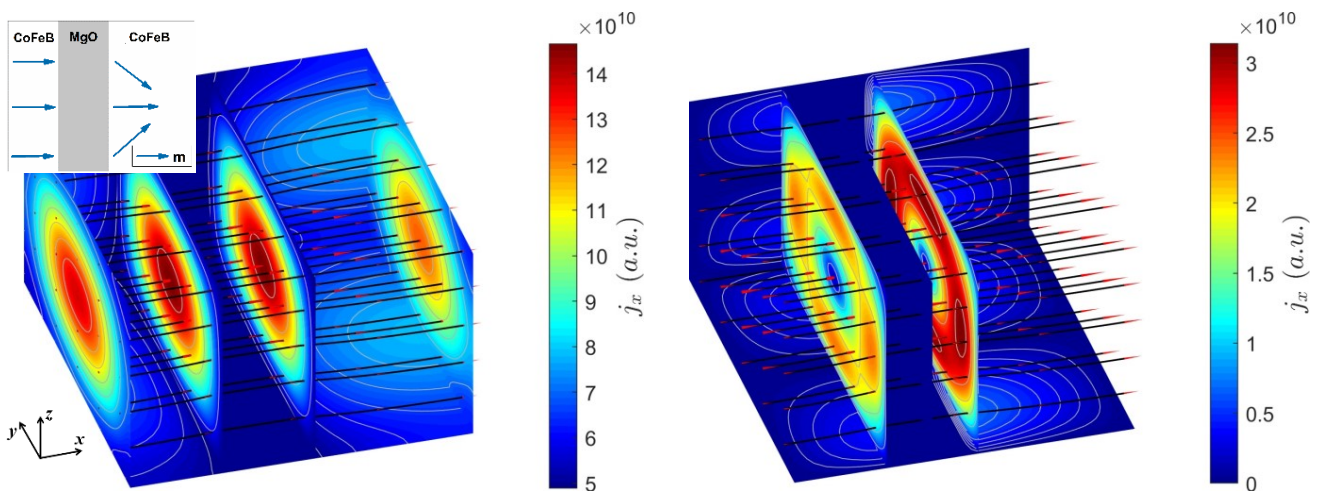


Fig. 1. Current density distribution through a square MTJ with a non-uniform magnetization (Inset). The left picture shows the x-component (perpendicular) of the current density, while the right pictures shows the module of the y- and z- (in-plane) components. The x-component flow is higher for aligned magnetizations due to lower resistance. Due to conservation of the current flow, it is redistributed in the yz plane in the metal contacts (right panel).

magnetization alignment and the corresponding local TMR, and compare the results with the switching at a fixed voltage. We define the voltage at which the switching is performed to be equal to the current multiplied with the tunnel junction's resistance in the initial P or AP state.

II. MODEL

The key element of any modern MRAM cell is an MTJ. It consists of two ferromagnetic layers, typically CoFeB, separated by a thin tunnel barrier. MgO is mostly used to create the tunnel barrier as it provides a high TMR. The TMR is defined as

$$TMR = \frac{R_{AP}-R_P}{R_P}, \quad (1)$$

where R_P (R_{AP}) is the resistance in the P (AP) MTJ state. Achieving a high TMR is important in order to reliably discern between the P and the AP configuration. The use of an in-plane CoFeB/MgO/CoFeB MTJ provides a TMR up to 600% [6].

In addition, due to the interface-induced perpendicular anisotropy, thin layers of CoFeB on MgO are perpendicularly magnetized. In this configuration, the switching path and the thermal relaxation paths for the magnetization coincide, leading to lower switching currents as compared to in-plane magnetized structures. The stable magnetization of the layers has two possible configurations: parallel and anti-parallel. The magnetization in the free layer can switch, while the magnetization in the second reference layer is fixed by the exchange coupling to the pinned layer [7].

The equation which describes the magnetization dynamics is the Landau-Lifshitz-Gilbert (LLG) equation, with the corresponding torques. With the STT torque \mathbf{T}_S added, the LLG equation reads as [8]

$$\frac{\partial \mathbf{m}}{\partial t} = -\gamma \mathbf{m} \times \mathbf{H}_{\text{eff}} + \alpha \mathbf{m} \times \frac{\partial \mathbf{m}}{\partial t} + \frac{1}{M_S} \mathbf{T}_S \quad (2a)$$

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

where $\mathbf{m} = \mathbf{M}/M_S$ is the position-dependent normalized magnetization in the free layer, M_S is the saturation magnetization, α is the Gilbert damping constant, γ is the gyromagnetic ratio, \hbar is the reduced Plank constant, e is the electron charge, J_C is the current density, P is the spin current polarizing factor [9] assumed to be equal in both ferromagnetic layers, d is the thickness of the free ferromagnetic layer, θ is the angle between local magnetization vectors in the free and fixed layer, and \mathbf{x} is the unit vector along the fixed layer magnetization (Fig. 1, inset). The effective magnetic field \mathbf{H}_{eff} includes the external field, the magnetic anisotropy field, the Ampere field, the demagnetizing field and the stray field from the reference layer/magnetic stack. To model the switching at finite temperature, \mathbf{H}_{eff} also includes a thermally fluctuating stochastic magnetic field.

The standard approach to simulate STT switching is to assume a position-independent current density J_C [4]. For low TMR, when the resistance difference between the low and high resistance configuration is small, this assumption can be

justified for in-plane MTJs [10]. However, modern MTJs are perpendicularly magnetized (p-MTJs) and possess a large TMR around 200%. In this case the simplified description offered by (2b) is not accurate. When current is flowing, the local magnetization vectors along the free layer are not collinear. This results in a position-dependent current density, which in turn leads to position-dependent spin currents and spin torques.

In order to evaluate the behavior of the current in a scenario with non-uniform magnetization in the free layer, we compute the current density flowing through the MTJ structure as

$$\mathbf{J}_C = -\sigma \nabla V. \quad (3)$$

The electric potential V in the metal ferromagnetic contacts is found by solving the Laplace equation $\nabla^2 V = 0$. The local conductance of the barrier is taken as suggested in [9].

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

In Fig.1 we show the current density for the magnetization configuration schematized in the inset. The current density is highly inhomogeneous in order to accommodate the varying conductance across the barrier.

As the fixed voltage leads to a non-uniform current density distribution, the impact of assuming a fixed voltage in switching simulations must be evaluated.

III. RESULTS

We compare the model with a *fixed voltage* across the MTJ and the *constant current density* described by (2) to the reference model [10] generalized to p-MTJs, in which the *total current* is fixed but *redistributed* over time according to the local resistance value. The simulations are performed for a p-MTJ. The system's parameters are set to typical experimental values [11]. The stack is of a pillar shape of 40 nm diameter. The thicknesses of the free and the reference CoFeB layers are 1.7 nm and 1 nm, respectively. The thickness of the MgO layer is 1 nm.

At room temperature the switching times depend on the realization of the stochastic magnetic field mimicking the magnetization fluctuations. As shown in Fig.2, the average switching times assuming a fixed current or a fixed current density are very similar for both P to AP and AP to P switching. However, the switching for the fixed, constant voltage, with its value chosen so that the initial current before the switching is the same, looks very different [12]. The difference is due to the fact that, when assuming a fixed voltage, the current depends on the varying resistance of the MTJ. In order to compensate the effect of the varying resistance, the current value under the assumption of a fixed current must be increased by ~9% for AP to P and decreased by ~4% for P to AP switching, for a TMR of 200%.

Fig.3 demonstrates that after correcting the current the switching times as a function of the stray field within the fixed voltage and the fixed current approach are the same. The dependence of the current correction on TMR is shown in Fig.4. The results imply that the constant current density assumption is justified in the realistic case of switching at a constant voltage at *room temperature*, provided that the current is appropriately corrected for the P to AP and the AP to P scenario.

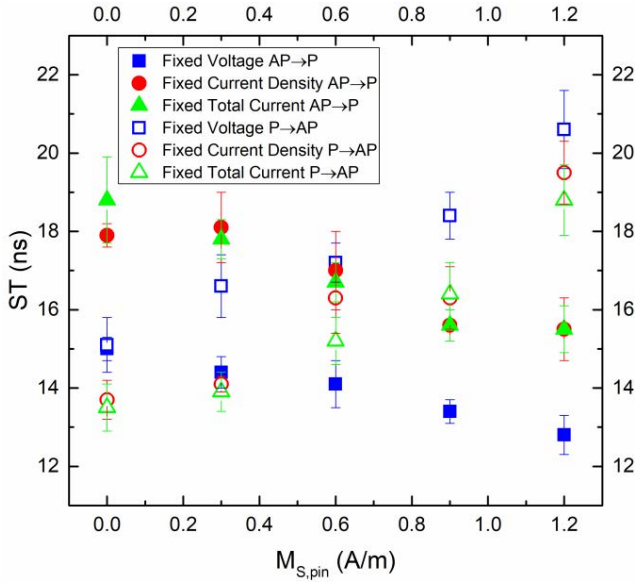


Fig. 2. Comparison between AP→P and P→AP switching for various levels of the uncompensated stray field at $T=300$ K. Filled symbols represent P→AP switching, empty ones AP→P. The bars show ST variations due to thermal fluctuations.

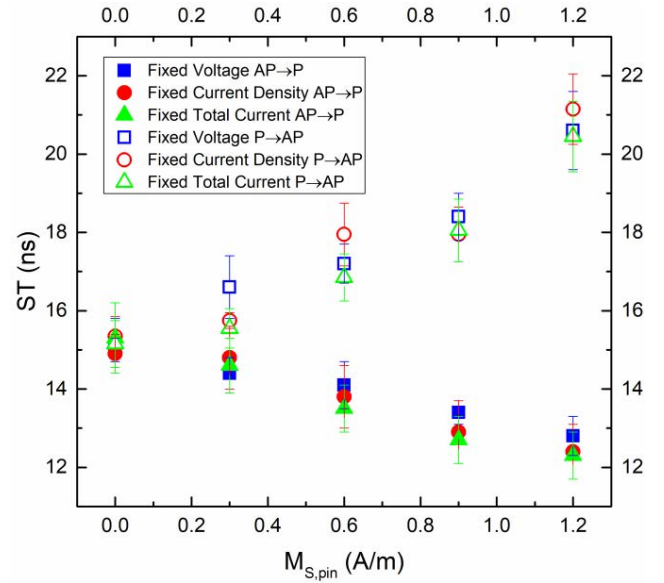


Fig. 3. Comparison of switching times for the tuned values of input currents at $T=300$ K. The switching times of all three models are compatible within the thermal variation.

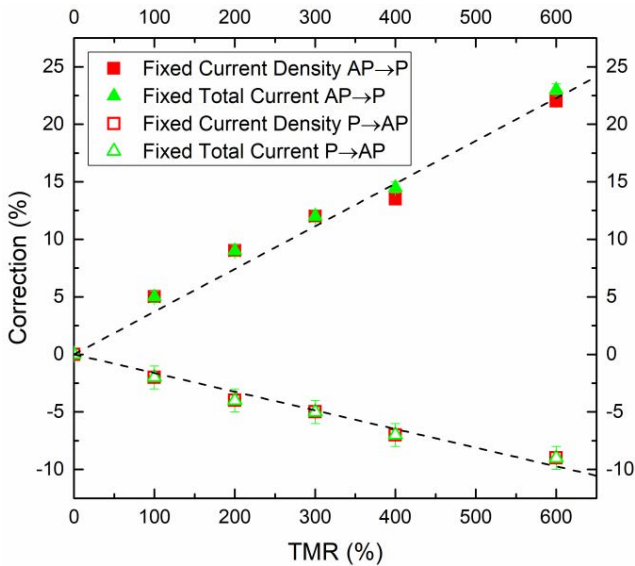


Fig. 4. The correction to the current as a function of TMR at $T=300$ K, which must be given in order for all three models to give consistent results, for both P→AP and AP→P switching. The dashed lines represent a linear fit.

In order to further elaborate on the origins and magnitude of the current correction, we performed the calculations at zero temperature. The switching times assuming a fixed current or a fixed current density are indistinguishable. As in the case of room temperature, the results for the switching times under the assumption of a fixed voltage differ from those with the fixed current, if the voltage is equal to the current times the initial resistance. However, with the appropriate current correction, all three models provide similar results (Fig.5).

The current correction is smaller than the one obtained at room temperature. We also note that the switching is slower at zero temperature (Fig.6). Therefore, the current correction is not universal and depends on the external parameters.

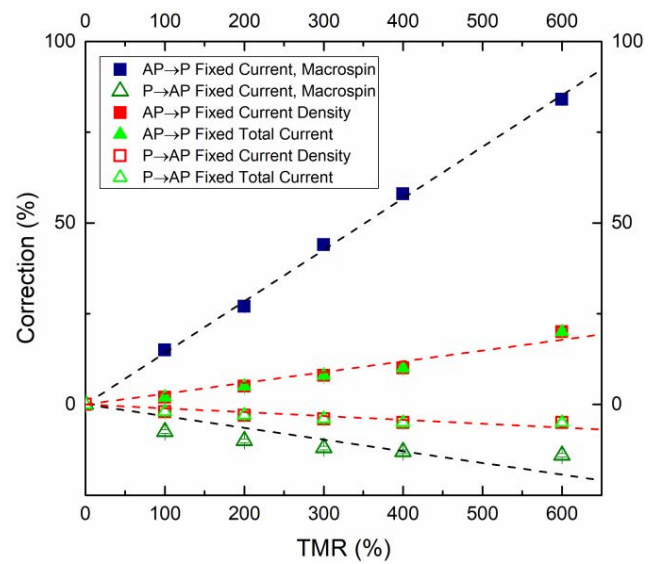


Fig. 5. Correction to the current as a function of TMR at $T=0$ K, for both the micro- and macrospin case. The amount of correction differs between the two cases, due to the differing switching times.

In order to elaborate on the possible reasons for this dependence, we performed a macrospin simulation. We carry out the simulations at zero temperature. In order to achieve the STT switching, we slightly deviate the initial angle of the macrospin from the perfect perpendicular orientation.

Fig.7 demonstrates that the switching process with the fixed voltage is steeper for AP to P switching than that with the fixed current. In order to compensate for the gradual slope at fixed current, the switching must start earlier, which is achieved by increasing the current. For the switching in the opposite direction the trend is the reverse: the fixed current model is steeper. Therefore, we need to lower the current to make the switching start later and compensate for the difference in slope by decreasing the current.

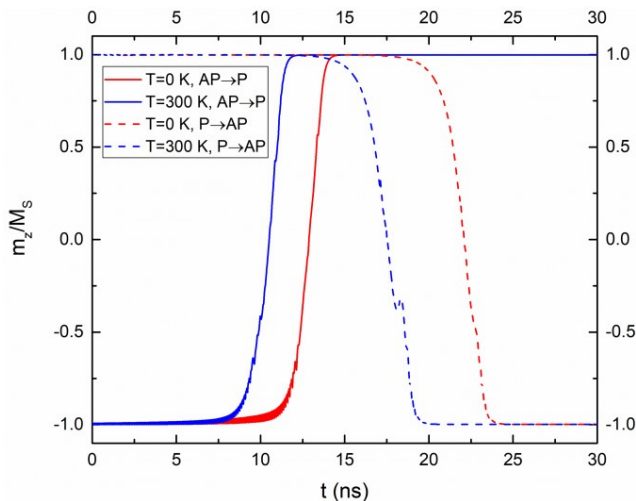


Fig. 6. Comparison between switching realizations for the fixed voltage model, with TMR=200%, at $T=0$ K and $T=300$ K. The switching is slower at low temperature.

We can explain this behavior with the help of equations (1)-(3). In the model with the fixed voltage the dependence of the current on the magnetization configuration completely compensates the angular dependence in the torque, so the torque remains constant at switching.

Under the fixed current assumption the torque is maximal at the beginning of AP to P switching, when it is the same as under the fixed voltage assumption. The torque becomes weaker as the configuration proceeds towards P. This trend must be compensated by a current correction to increase the current. The scenario is opposite for the case of P to AP switching, in agreement with Fig.7. The torque is minimal at the beginning and becomes stronger as the configuration proceeds towards AP, and the trend is compensated by a weaker current.

Within the macrospin model the current correction amplitude must increase, if the switching is faster, as shown in Fig. 7, Inset. As the average switching time is shorter at room temperature, it explains a slightly larger current correction required to match the results for switching times from all three models at $T=300$ K as compared to the simulations at $T=0$ K.

IV. CONCLUSION

We compared the switching time distribution obtained under the assumption of a fixed voltage across the structure to the results of two approximations of switching under fixed current and fixed current density constraints. We showed that a TMR and voltage-dependent correction of the fixed current values is required to correctly reproduce the switching time distribution in a broad TMR range. The current correction is not universal and depends on the switching time and temperature, in agreement with the macrospin model. As soon as the current correction is introduced, the simple constant current density approach reproduces correctly the switching time distribution and allows to obtain results very fast.

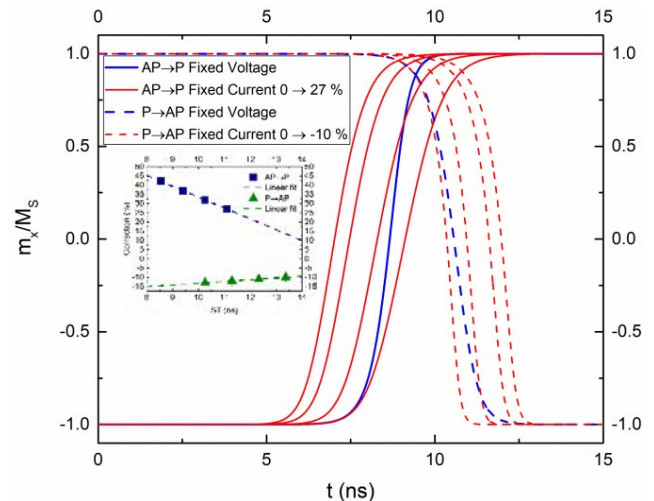


Fig. 7. Switching realizations in the Macrospin case for the fixed voltage and fixed current density models, with different values of correction. The inset shows how a faster switching leads to an increased amount of correction.

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