Comprehensive Modeling of Coupled Spin and Charge Transport through Magnetic Tunnel Junctions

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***Abstract*—A drift-diffusion approach to coupled spin and charge transport has been commonly applied to determine the spin-transfer torque acting on the magnetization in metallic valves. This approach, however, is not suitable to describe the predominant tunnel transport in magnetic tunnel junctions. Here we demonstrate that by introducing a magnetization dependent resistivity and adjusting the spin diffusion coefficient one can successfully apply the generalized spin-charge drift-diffusion approach also for magnetic tunnel junctions. As a unique set of equations is used for the entire structure this paves the way to develop an efficient finite element based approach to describe the magnetization dynamics in emerging spin-transfer torque memories.**

Keywords – Spin and charge drift-diffusion, spin-transfer torque, magnetic tunnel junctions, STT-MRAM

Spin-transfer torque magnetic RAM (STT-MRAM) is an emerging [1-6] non-volatile memory which possesses a simple structure and is compatible with CMOS technology. In contrast to flash memory, STT-MRAM is fast and has a high endurance. It makes it particularly suitable for stand-alone as well as embedded applications, for example, in Systems-on-Chip, where STT-MRAM is poised to replace slow SRAM and flash memories.

Accurate design of STT-MRAM demands a solution of the Landau-Lifshitz-Gilbert equation describing the magnetization $\mathbf{m}$ subject to the spin-transfer torque. The torque $\mathbf{T_S}$ is created by a nonequilibrium spin accumulation $\mathbf{S}$ acting on the magnetization via the exchange interaction and can be expressed as

$$\mathbf{T_S} = -\frac{D_e}{\lambda_J^2}\mathbf{m}\times\mathbf{S} - \frac{D_e}{\lambda_\varphi^2}\mathbf{m}\times(\mathbf{m}\times\mathbf{S}), \quad (1)$$

where λ_J, λ_φ, are scattering lengths and D_e is the electron diffusion constant. $\mathbf{S}$ is created, when a current passes through the structure. In order to obtain $\mathbf{S}$, coupled spin and charge transport must be resolved.

This task is performed by solving the spin and charge drift-diffusion equations in a *spin valve*, where the two ferromagnetic layers are separated by a *metal* [7], [8]. However, the cell of an STT-MRAM represents a *magnetic tunnel junction* (MTJ), a sandwich of two ferromagnets separated by a *tunnel barrier*. The tunnel barrier ensures a high tunnel magnetoresistance ratio (TMR) related to the large difference in the resistances R_P and R_{AP} in the parallel/anti-parallel MTJ configuration.

$$\text{TMR} = \frac{R_{AP}\text{-}R_P}{R_P}. \quad (2)$$

The tunnel resistance defines the current through an MTJ as it is much larger than the resistances of the ferromagnetic layers. For non-uniform relative magnetization, characteristic to switching (Fig.1), the resistance and the current through an MTJ depends strongly on the position. As Ohm's law must hold, the physical origin resulting in the electrical resistivity is not important. We assume it to be due to charge drift-diffusion in the middle layer. We then model the tunnel barrier as a (poor) conductor whose (large) resistivity depends on the ***relative orientation of the magnetization***. This results in highly non-uniform current density (Fig.2), provided the voltage at the contacts is fixed.

It is not sufficient to match the electrical characteristics to correctly model the properties of a tunnel barrier. The spin accumulation density must be preserved in case of electrons tunneling through an ideal barrier without spin flips. Provided the current density $\mathbf{J_C}$ is known, the spin accumulation and the spin current density $\mathbf{J_S}$ are found as [8], [9]:

$$\mathbf{J_S} = \frac{\mu_B}{e}\beta_\sigma\left(\mathbf{J_C} + \beta_D D_S \frac{e}{\mu_B}[(\nabla\mathbf{S})\mathbf{m}]\right)\otimes\mathbf{m} - D_S\nabla\mathbf{S} \quad (3)$$

$$\frac{\partial\mathbf{S}}{\partial t} = -\nabla\mathbf{J_S} - D_S\left(\frac{\mathbf{S}}{\lambda_{sf}^2} + \frac{\mathbf{S}\times\mathbf{m}}{\lambda_J^2} + \frac{\mathbf{m}\times(\mathbf{S}\times\mathbf{m})}{\lambda_\varphi^2}\right) \quad (4)$$

μ_B is the Bohr magneton, e is the electron charge, β_σ and β_D are polarization parameters, D_S is the spin diffusion constant, λ_{sf} is the spin-flip length, and $\otimes$ stands for the tensor product. To preserve the spin accumulation through the middle layer, one must neglect the spin relaxation by setting all scattering lengths to infinity. However, this is not sufficient. In Fig.3 we show the spin accumulation computed via the finite element approach. In order to match the spin accumulation throughout the tunnel barrier within the spin drift-diffusion approach, the ***spin diffusion coefficient*** in the middle region must be set ***large*** compared to the electron diffusion coefficient in the ferromagnetic layers. With $\mathbf{S}$ known, we compute the torques acting on both ferromagnetic layers, which are reported in Fig.4. Finally, Fig.5 shows the dependence of the torque acting on the free layer on the choice of the spin diffusion coefficient. Provided that the value of the latter is large enough, the torque is independent of it.

We conclude that the generalized spin-charge drift-diffusion approach presented here can be successfully applied to determine the spin accumulation and torques acting in an MTJ structure.

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REFERENCES

[1] S.Aggarwal *et al*., Proc. IEDM, 2.1.1 (2019).

[2] K.Lee *et al*., Proc. IEDM, 2.2.1 (2019).

[3] V.B.Naik *et al*., Proc. IEDM, 2.3.1 (2019).

[4] J.G.Alzate *et al*., Proc. IEDM, 2.4.1 (2019).

[5] G.Hu *et al*., Proc. IEDM, 2.6.1 (2019).

[6] W.J.Gallagher *et al*., Proc. IEDM, 2.7.1 (2019).

[7] C.Abert *et al*., Sci. Rep. 5, 14855 (2015).

[8] S.Lepadatu, Sci. Rep. 7, 12937 (2017).

[9] S.Fiorentini *et al.,* Proc. SISPAD, 57 (2019).

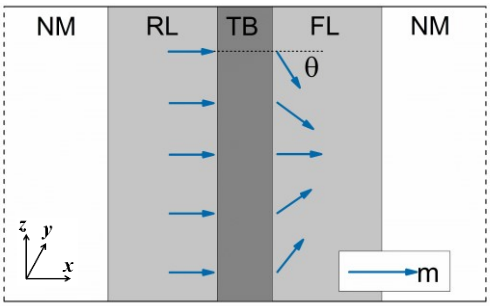

Figure 1. MTJ structure with non-uniform magnetization configuration. The structure is composed of reference layer (RL), tunnel barrier (TB), free layer (FL), and two non-magnetic contacts (NM).

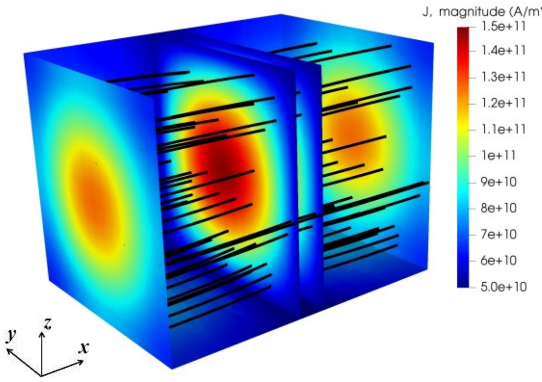

Figure 2. Current density through the MTJ. The current is redistributed towards the region of highest conductivity.

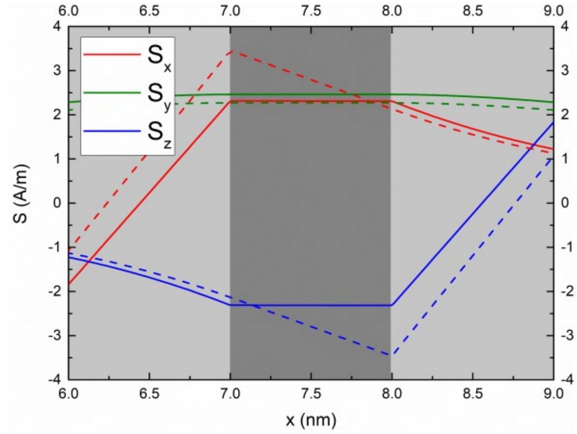

Figure 3. Spin accumulation across the tunneling layer. The magnetization lies along x in the FL and along z in the RL. The dashed lines are computed using the same value for D_S in TB and D_e in the FL and the RL, while solid lines use a very high value of D_S, which renders **S** constant across TB.

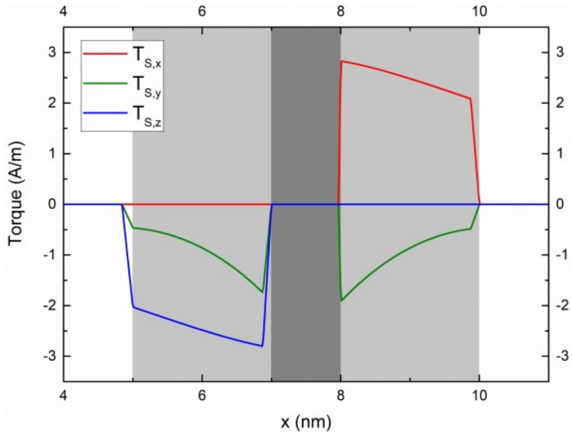

Figure 4. Shape of the torque computed from the spin accumulation. The spin drift-diffusion approach permits to compute the torques acting on both layers, FL and RL.

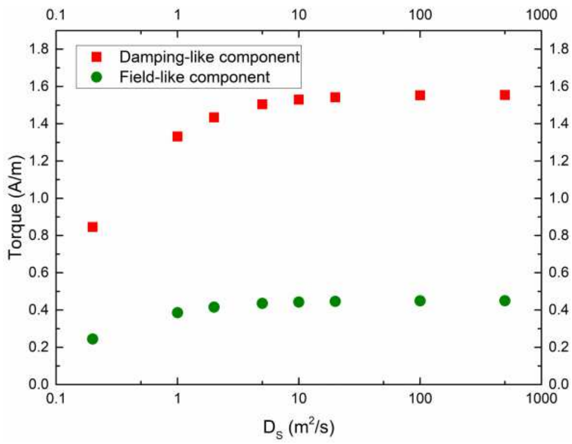

Figure 5. Magnitude of the torque in the FL as a function of the spin diffusion coefficient in TB. At high values of the coefficient, the torque does not depend on it.