Boundary conditions for micromagnetism with spin currents

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Spin Hall torque devices, composed by a ferromagnet (F) and a normal metal (N), are among the most promising development of spintronics. Examples are the spin Hall torque memories in which the spin current generated by the spin Hall effect of the metal is able to exert a torque and switch the magnetization of the ferromagnet [1], and the spin pumping effect, in which, at the ferromagnetic resonance, a DC spin current is injected into the metal and revealed by the inverse spin Hall effect [2]. In both cases a spin current is generated and absorbed by the two layers. From the theoretical point of view it would be desirable to extend the theory of micromagnetism in order to account for the spin current. This task has been brought forward on the one side by setting the boundary conditions for the spin potential [3] and on the other side by coupling the spin diffusion models with micromagnetics [4]. The first approach is the most common one, but has the drawback to treat the ferromagnet with uniform magnetization and to introduce a parameter, the spin mixing conductance, of difficult physical interpretation. The second approach has the merit to couple the micromagnetic dynamic equation with an additional equation for the spin accumulation, but has the limit to lack the notion of the spin potential that is relevant in a thermodynamic formulation. Alternative approaches consider that the notion of spin current is unclear and should be avoided [5]. In ferromagnets it is expected that any magnetic moment current with moments in the direction perpendicular to the magnetization is rapidly absorbed [3]. In this paper, to account for the transverse spin current, we introduce modified boundary conditions of micromagnetics. If we have an energy flow from the boundaries, we expect that the Brown's, adiabatic, boundary conditions should be modified. We start by the definition of the constitutive equations of the spin currents in non magnetic metals [6] and derive consequent generalized boundary conditions for micromagnetics. As a result we get a definition of the magnetic moment current valid at the boundary of the ferromagnet:

$$\mathbf{j}_{\mathbf{M},\perp} = \mu_0 \gamma_L M_s^2 l_{EX}^2 (\mathbf{m} \times \nabla \mathbf{m} - \alpha \nabla \mathbf{m}) \tag{1}$$

where μ_0 is the magnetic constant, γ_L the gyromagnetic ratio, M_s the saturation magnetization, l_{EX} the exchange length, α the damping, $\mathbf{m}$ is the magnetic versor and $\perp$ means in the plane perpendicular to $\mathbf{m}$. This definition, together with the associated spin potential, allows to set and solve problems with different F/N layers where the value of the current at the F side should be equal to the value at the N side. In this paper, as an example of application, we study the injection of a transverse spin current in the limit of bulk ferromagnet and the spin Hall torque and spin pumping effects in the limit of thin ferromagnetic films and we compare the results with experiments [7]. The method proposed can be, in perspective, employed in numerical calculations of extended structures.

References

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