Spin-Transfer Torques in Ferromagnetic and Antiferromagnetic Systems with Spin-Orbit Interaction

We formulated a general microscopic approach to spin-orbit torques in thin ferromagnet/heavy-metal and antiferromagnet/heavy-metal bilayers in linear response to electric current or electric field. The microscopic theory we develop avoids the notion of spin currents and spin-Hall effect. Instead, the torques are directly related to a local spin polarization of conduction electrons, which is computed from generalized Kubo-Streda formulas.

The dynamic response of magnetization to electric currents flowing in the system is an interesting problem that has numerous applications. The rise of ferromagnetic, and recently antiferromagnetic, spintronics that promises controllable ferromagnetic or antiferromagnetic (AFM) domain switching with particularly low currents adds a number of challenges in the field. At the same time, the ferromagnetic (FM) layers on the top of heavy-metal materials like Pt continue to be developed to become more sensitive to in-plane electric currents, see Fig. 1. Phenomenological approaches to spin torques, which have been proposed so far, ignore the role of spin-orbit interaction. An additional complexity arising in antiferromagnetic systems makes phenomenological approach even less useful since the underlying system symmetry is so complex that the number of free phenomenological parameters in such theories tends to infinity.

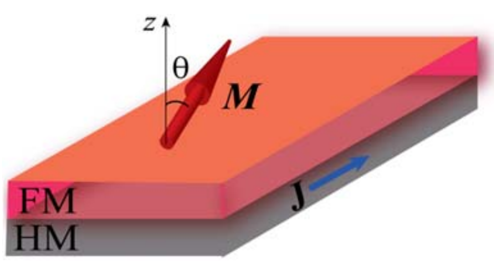

Fig. 1 Schematic of the studied system.

On the contrary, we use a microscopic approach, where we employ the framework of an *s-d* model, i.e. we separate a subsystem of localized spins (“d-electrons”) in the FM or AFM system from the subsystem of itinerant (conduction) electrons (or “s-electrons”). The magnetization dynamics of the FM subsystem is then investigated on the basis of the local mean field approach. The main idea of this approach f FM with localized spins is described by a classical magnetization field with constant length. The ground state of the FM is determined by the minimum of the free energy, which disregards the effects of itinerant electrons. The Landau-Lifshitz-Gilbert equation for the magnetization dynamics in this approach is governing this process.

We have shown that a unique dissipative-torque does not exist in a system with spin-orbit interaction. Instead, the lower symmetry of the model with Rashba interaction leads to the decomposition of the torques [1]. Moreover, the presence of spin-orbit interaction can increase the amplitude of dissipative spin-orbit torques by orders of magnitude. These and other consequences of the simple symmetry analysis based on microscopic models may have a predictive power that is absent as a matter of principle in a phenomenological approach to the problem. The results can be reproduced by a kinetic equations based on the Boltzmann-like equation for the lesser Green function. This allows us for the first time to consider the torques acting on magnetization independent of the angle between magnetization and two-dimensional plane of the heavy-metal layer.

In a follow-up we would like to extend the analysis to simple two-dimensional antiferromagnets (AFM) with spin-orbit interaction. The need for such a research is dictated by the fast development of AFM applications that involve current-induced AFM domain switching, e.g. the active development of the AFM MRAM devices that utilize heavy-metal/AFM bilayers. Our analysis will serve as an important benchmark to test kinetic equation methods and various numerical approaches to the problem that will be developed to treat realistic AFM devices.

References

[1] I. A. Ado, Oleg A. Tretiakov, and M. Titov, Phys. Rev. B **95**, 094401 (2017).

Keywords: spintronics, magnetic, texture
Mikhail Titov (Radboud University, Nijmegen, The Netherlands)
E-mail: m.titov@science.ru.nl
http://www.bauer-lab.imr.tohoku.ac.jp/