# Direct and inverse spin-orbit torques from first principles

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Under application of electric currents, ferromagnetic (FM) layers asymmetrically sandwiched between nonmagnets (NM1, NM2) in NM1/FM/NM2 films experience spin-orbit torques (SOTs) on the magnetization, which can serve to switch the magnetic state of the FM layers. Using density-functional theory calculations we study SOTs by means of the Kubo linear response formalism [1]. Comparing SOTs in NM1/FM films for different choices of NM1 (Pt, W, Ta, Ir, Au) we show that the sign of the spin Hall effect in these transition metals correlates with the even ("damping-like") component of SOT. Resolving torques and spin-fluxes on the atomic scale allows us to elucidate further the role of spin-currents in mediating the SOTs and to identify an additional spin-current independent component. Varying the thickness of the Co and Pt layers as well as the choice of NM2 in NM2/Co/Pt(111) films we find a strong sensitivity of the odd ("field-like") component of SOT, while the even component is less sensitive. Estimating extrinsic contributions from a scalar disorder model [2] we argue that intrinsic effects prevail. Our results on the NM2/Co/Pt(111) systems are in very good quantitative agreement with recent experiments [3] on AlO/Co/Pt(111) films.

Besides the direct SOT also its inverse effect is currently of great interest. While the direct SOT allows us to control the magnetization via applied electric current pulses, the inverse effect consists in the generation of current in the presence of a time-dependent magnetization. We discuss exact relationships between direct and inverse SOTs within the Kubo linear response formalism. An important contribution to the inverse SOT is the conversion of pumped spin current into charge current via the inverse spin Hall effect. We focus in particular on the spatial decay in the NM1 layer of the spin current pumped into NM1 via the ferromagnetic resonance of the FM layer and its conversion into a charge current, which is a question that so far has been addressed only within phenomenological models. Finally, we consider the adiabatic inverse SOT, which allows us to relate the intrinsic even SOT to the Dzyaloshinskii-Moriya interaction [4,5].

[1] F. Freimuth et al., arXiv:1305.4873

[2] J. Weischenberg et al., PRL 107, 106601 (2011)

[3] K. Garello et al., Nature Nanotechnology 8, 587-593 (2013)

[4] F. Freimuth et al., J. Phys.: Condens. Matter 26 (2014) 104202

[5] F. Freimuth et al., Phys. Rev. B 88, 214409 (2013)