MAGNETIZATION DYNAMICS OF MAGNETIC NANOSTRUCTURES WITH STRONG SPIN-ORBIT INTERACTION

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There is much current interest in dynamical processes in magnetically ordered systems both from scientific and technological viewpoints. The special interest is related to the problem of the intercoupling between a spin-polarized electron current and the magnetization dynamics in multilayer magnetic nanostructures that can be exhibited in such phenomena, as magnetic switching and a sustained precession of magnetic order vectors. Such phenomena have real potential for application in systems of high-speed magnetic processing information and high frequency fine-tuned GHz and THz electromagnetic radiation [1-3].

The electric-controlled magnetization assumes the conversion the input electric current into a spin current, origin of which dependences on the effective internal magnetic bias fields. The latter can be related to interactions both an exchange interaction in magnetic medium and a spin-orbit interaction. The current-controlled magnetization dynamics (including the magnetic switching and precession) is realized through the exchange interaction of the spin current with localized magnetization with the spin torque on the latter. The combination of such the current-controlled magnetization with magnetoresistive effects (tunnel and anisotropy magnetoresistive effects) permit to convert magnetization variations into a coherent microwave radiation realizing based on the multilayer magnetic nanostructures. The radiation frequency is determined by the internal effective magnetic field providing the magnetization oscillation. Such the effective field in the ferromagnetic nanostructures provides the radiation frequency in the range MHz–GHz. For antiferromagnetic based nanostructures this range includes THz, that is caused by the large magnitude of the antiferromagnetic exchange interaction between magnetic sublattices and consistently, by the large internal effective magnetic field. Therefore, the prospect of increasing of the operation frequencies is related to ferri- and antiferromagnetic based magnetic nanostructures. In addition, decreasing the threshold current density for the magnetization excitation, a low-energy consumption at high operation speed are related to the spin-orbit generation of the controlling spin current and the corresponding spin-orbit torque (SOT).

Spin-orbit torqueses rely on the spin-orbit mediated exchange of angular momentum between the crystal lattice and the magnetization in the presence of an electric field. It was recently found that they are able to switch the magnetization in ferromagnetic bilayers [2, 3], and have attracted considerable interest for technological applications in the field of magnetic random access memories. Two different mechanisms have been suggested that give rise to SOT in bilayers consisting of a heavy metal substrate and a thin ferromagnetic layer deposited on top of it. The first mechanism is attributed to the spin Hall effect [2] which generates a spin current from the substrate towards the ferromagnet. The second mechanism is due to the generation of a current-induced spin accumulation at the interface between the two materials, where magnetism, spin-orbit coupling and broken inversion symmetry coexist. While the spin Hall conductivity of the heavy metal is a rather robust quantity, the current-induced spin accumulation generally depends very sensitively on the details of disorder at the interface.

The characteristic features of the spin-orbit torque can be described in the framework of the *s-d* model Hamiltonian

$$H = \left(\frac{\boldsymbol{p}^2}{2m} + V(\boldsymbol{r}) \right) - J_{sd} (\boldsymbol{s} \cdot \boldsymbol{S}_d) + \frac{1}{mc^2} \left[\nabla V \times \boldsymbol{p} \right] \boldsymbol{s} \, ,$$

where the first bracket separated expression is the sum of kinetic and potential energy, the second term is the *s-d* exchange interaction between itinerant electron spin $\boldsymbol{s}$ and the localized spin $\boldsymbol{S}_d$. Introduction the spinor wave function $\Psi(\boldsymbol{r},t)$, spin current density magnetization $\boldsymbol{m} = \Psi^*(\boldsymbol{r},t)\boldsymbol{s}\Psi(\boldsymbol{r},t)$ and current density $\boldsymbol{J}_s = -(\hbar/m)\left[\Psi^*(\boldsymbol{r},t)\boldsymbol{s}\nabla_{\boldsymbol{r}}\Psi^*(\boldsymbol{r},t)\right]$ give equations, which after a quantum-mechanical averaging take on form

$$\frac{d\boldsymbol{m}}{dt} = \nabla J_s - \frac{J_{ex}}{\hbar} \boldsymbol{M} \times \boldsymbol{m} + \frac{1}{mc^2} < \left[\nabla V \times \boldsymbol{p} \right] \times \boldsymbol{s} >,$$

$$\frac{d\boldsymbol{M}}{dt} = -\gamma \boldsymbol{M} \times \boldsymbol{H} + \alpha \boldsymbol{M} \times \frac{d\boldsymbol{M}}{dt} + \frac{J_{ex}}{\hbar} \boldsymbol{M} \times \boldsymbol{m},$$

where $\boldsymbol{M}$ is the unite vector of the localized magnetization, $\boldsymbol{H}$ is the effective field, γ is the gyromagnetic ratio, α is the Gilbert damping. Here the latter term in the first equation describes the spin-orbit torque $\boldsymbol{T}$, which at a uniform magnetization ($\nabla J_s = 0$) takes the form

$$\boldsymbol{T} = \frac{J_{ex}}{\hbar} \boldsymbol{M} \times \boldsymbol{m} = \frac{1}{mc^2} < \left[\nabla V \times \boldsymbol{p} \right] \times \boldsymbol{s} > .$$

The spin-orbit torque can be represented as $\boldsymbol{T} = \boldsymbol{T}_{fl} + \boldsymbol{T}_{dl}$, where $\boldsymbol{T}_{fl}$ is the field-like torque originated from the spin-orbit coupling at the interface, in conjunction with the perturbation of electron distribution function, $\boldsymbol{T}_{dl}$ is the damping-like torque originated predominantly from the spin Hall effect, that is a consequence of the perturbation of electronic states by applied electric field.

LITERATURE

1. Zutic L., Fabian J., Das Sarma S. Spintronics: Fundamentals and applications. // Rev. Mod. Phys. – 2004. – v.76. – P.323–349.
2. Manchon A., Koo H.C., Nitta J., Frolov S.M,, Duine R.A. New Perspective for Rashba Spin-Orbit Coupling. // Nature Materials. – 2015. – v.36. – P.871–887.
3. Sinova J., Valenzuela S., Wunderlich J., Back C.H., Jungwirth T. Spin Hall Effects // Rev. Mod. Phys. – 2015. – v.87. – P.1213 – 1237.