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Dynamics of nonequilibrium conduction electrons in ferromagnetic metal layer in spin pumping experiments

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Spin pumping experiments play a key role in fundamental research in spintronics. The spin pumping effect, that is usually studied in ferromagnet/normal metal (F/NM) bilayers, originates from the exchange interaction between conduction electrons and localized electrons of magnetisation. The localized spins in the ferromagnetic layer precess under the ferromagnetic resonance (FMR). This precession is steadily transferred through the exchange interaction to the conduction electrons that propagate due to diffusion motion into the metal layer resulting in the pure spin current without electric charge transfer. This phenomenon underlies many different spintronic technologies.

In this work we develop a new theoretical model, based on classical diffusive equations, to describe the effect of spin pumping in bilayers with a ferromagnetic metal (FM) layer. The proposed model includes the effect of spin memory loss that arises due to possible spin relaxation at FM/NM interface. Within this model we have obtained explicit expressions for the nonequilibrium magnetization carried by the conduction electrons in ferromagnetic and metallic layers. It allowed us to obtain analytical expressions for the effective spin mixing conductance, inverse Edelstein effect and spin-memory loss parameter. Within our model we have also described for the first time the effect of self induced ISHE that was recently observed in permalloy and FeGaB.

We base our theoretical model on classical diffusive equation for the conduction electrons that was derived in [1] for the FM layer and in [2] for the NM layer. We consider that the sample is located in the xz plane, external magnetic field is directed along $\hat{z}$ axis. The spin current flows perpendicular to the plane of the sample along $\hat{y}$ axis. The thickness of the FM (NM) layer is t_F (t_N).

We use the boundary conditions at the edges of the sample ($y = -t_F$ and $y = t_N$) that displays the zero spin current

$$\begin{cases} \left.\dfrac{\partial \boldsymbol{\delta}\mathbf{m}}{\partial y}\right|_{y=-t_F} = 0, \\[2ex] \left.\dfrac{\partial \boldsymbol{\delta\mu}}{\partial y}\right|_{y=t_N} = 0. \end{cases} \tag{1}$$

At the FM/NM ($y = 0$) interface we use the following boundary conditions

$$\begin{cases} \left.\dfrac{\boldsymbol{\delta}\mathbf{m}}{\chi_F}\right|_{y=0} = \left.\dfrac{\boldsymbol{\delta\mu}}{\chi_N}\right|_{y=0}, \\[2ex] \left.\left(D_F\dfrac{\partial \boldsymbol{\delta}\mathbf{m}}{\partial y} + \beta\boldsymbol{\delta}\mathbf{m}\right)\right|_{y=0} = \left.D_N\dfrac{\partial \boldsymbol{\delta\mu}}{\partial y}\right|_{y=0}, \end{cases} \tag{2}$$

where $\boldsymbol{\delta}\mathbf{m}$ ($\boldsymbol{\delta\mu}$) is the nonequilibrium magnetization, D_F (D_N) is the diffusive constant, χ_F (χ_N) is the spin susceptibility of the conduction electrons in FM (NM) layer.

The first boundary condition was derived in [3]. This condition expresses the equality of free energy at FM/NM interface (see [3] for the details). The second one expresses the flow of a spin current across the interface with spin relaxation. The amplitude of the spin relaxation at the interface is given by the parameter β. We have introduced the spin relaxation at the interface in the similar way as it is done for the spin relaxation in the bulk of a metal layer. The amplitude of the spin relaxation at the interface should be found with the use of the quantum theory. Therefore, in this paper we fix the term with spin relaxation at the interface *ad hoc*.

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We have obtained the following solutions for the nonequilibrium magnetization in FM and NM layers

$$\boldsymbol{\delta\mu}(y) = -\frac{\mathrm{Re}\,[A]}{\cosh\left(\frac{t_N}{\lambda}\right)}\cosh\left(\frac{t_N - y}{\lambda}\right)\hat{\mathbf{M}}\times \times\frac{\partial\hat{\mathbf{M}}}{\partial t} + \frac{\mathrm{Im}\,[A]}{\cosh\left(\frac{t_N}{\lambda}\right)}\cosh\left(\frac{t_N - y}{\lambda}\right)\frac{\partial\hat{\mathbf{M}}}{\partial t}, \quad (3)$$

$$\boldsymbol{\delta m}(y) = -\,\mathrm{Re}\left[\frac{\bar{A}}{\sinh\left(\frac{t_F}{\Lambda}\right)}\cosh\left(\frac{t_F + y}{\Lambda}\right) - \bar{A}_0\right]\hat{\mathbf{M}}\times \times\frac{\partial\hat{\mathbf{M}}}{\partial t} + \mathrm{Im}\left[\frac{\bar{A}}{\sinh\left(\frac{t_F}{\Lambda}\right)}\cosh\left(\frac{t_F + y}{\Lambda}\right) - \bar{A}_0\right]\frac{\partial\hat{\mathbf{M}}}{\partial t}, \quad (4)$$

where $\Lambda = \sqrt{D_F\left(1/\tau_F - i/\tau_{ex}^F\right)^{-1}}$ is the complex spin diffusion length in ferromagnet (τ_{ex}^F describes the strength of the exchange interaction between localized and conduction electrons), λ is the spin diffusion constant in NM. The amplitudes of the nonequilibrium magnetization are expressed through the complex constants A, $\bar{A}$ and $\bar{A}_0$ which are given by

$$A = -i\frac{\chi_N}{\tau_{ex}^F D_F\gamma}\Lambda^2\frac{\lambda_{av}}{\Lambda_{\mathrm{eff}}\coth\left(\dfrac{t_F}{\Lambda}\right) + \lambda_{av}}, \quad (5)$$

$$\bar{A} = i\frac{\chi_F}{\tau_{ex}^F D_F\gamma}\Lambda^2\frac{\Lambda_{\mathrm{eff}}}{\Lambda_{\mathrm{eff}}\coth\left(\dfrac{t_F}{\Lambda}\right) + \lambda_{av}}, \quad (6)$$

$$\bar{A}_0 = i\frac{\chi_F}{\tau_{ex}^F D_F\gamma}\Lambda^2. \quad (7)$$

We have defined new effective spin diffusion lengths λ_{eff} and Λ_{eff} in order not to overload equations (5)–(7)

$$\lambda_{\mathrm{eff}} = \lambda\frac{D_F\chi_F + D_N\chi_N}{2D_N\chi_N}, \quad (8)$$

$$\Lambda_{\mathrm{eff}} = \Lambda\frac{D_F\chi_F + D_N\chi_N}{2D_F\chi_F}. \quad (9)$$

The effect of the spin relaxation at the FM/NM interface is expressed by the constant λ_{so} that can be considered as an effective spin diffusion length at the FM/NM interface

$$\lambda_{so} = \frac{D_F\chi_F + D_N\chi_N}{2\beta\chi_F}. \quad (10)$$

The spin diffusion length λ_{so} plays the similar role as the spin diffusion length in the metal layer. As it was mentioned earlier, the spin relaxation at the interface was introduced in the similar way to the relaxation in the bulk. Therefore, we will use the averaged spin diffusion length that takes into account the relaxation both at the interface and in the bulk of a metal layer

$$\lambda_{av} = \frac{\lambda_{so}\lambda_{\mathrm{eff}}}{\lambda_{so}\tanh\left(\frac{t_N}{\lambda}\right) + \lambda_{\mathrm{eff}}}. \quad (11)$$

This notation gives possibility to consider easily the case without interface spin relaxation if one substitutes in solutions $\lambda_{av} \to \lambda_{\mathrm{eff}}\coth\left(\frac{t_N}{\lambda}\right)$. At the same time we can consider the case of the spin pumping in the single ferromagnetic layer when only spin relaxation at the layer interface plays role $\lambda_{av} \to \lambda_{so}$. Such situation is realized in experiments on self-induced inverse spin Hall effect that are discussed below.

The complex amplitudes A and $\bar{A}$ set the inhomogeneous nonequilibrium magnetization in the bulk of FM. The term proportional to the amplitude $\bar{A}_0$ describes the nonequilibrium magnetization of the conduction electrons in the single ferromagnetic layer evenly distributed over the sample. This term coincides with [1] where the boundary conditions were neglected.

Solutions (3)–(7) for the nonequilibrium magnetization in FM/NM bilayers are the main result of the paper. It describes the evolution of the nonequilibrium magnetization under the spin pumping conditions. Using these equations we reproduce the main results for the spin pumping in heterostructure. The advantage of the used approach and corresponding solutions for the nonequilibrium magnetization is that it allows one to express all physical quantities in terms of fundamental constants, that can be useful in an analysis of the experimental data.

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