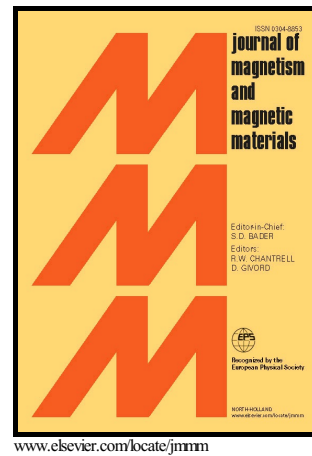


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Resonance excitation of the spin-wave current in hybrid structures

I.I. Lyapilin, M.S. Okorokov, N.G. Bebenin

*IMP, UB RAS, Ekaterinburg, Russia
Lyapilin@imp.uran.ru*

Abstract

Using the non-equilibrium statistical operator method (NSO), we have investigated the spin transport through the interface in a semiconductor/ferromagnetic insulator hybrid structure. We have analyzed the effective parameters approximation, when each of the considered subsystems (conduction electrons, magnons, and phonons) is characterized by its effective temperature. We have constructed the macroscopic equations describing the spin-wave current caused by both the resonantly exciting spin subsystem of conduction electrons and an inhomogeneous temperature field in the ferromagnetic insulator. We have shown that the spin-wave current excitation under combined resonance conditions exhibit a resonant nature.

Keywords: thermoelectric effect, spin current, resonance

PACS: 72.15 -b, 71.15

One of the central issues of spintronics is the development of new methods of generation and control spin currents in solids. There are different methods to implement the spin current: optical, magnetic, and what is particularly important for use in various devices, by an electric current. Usually an external perturbation acts on kinetic degrees of freedom. The spin-orbit interaction (it couples translational (kinetic) and spin degrees of freedom) plays a main role to form the resulting spin response. The latter can be exemplified by the spin Hall effect (SHE) [1],[2] that is exhibited as a spin current perpendicular to a charge current. It is the effect that is chiefly applied to create spin accumulation of conduction electrons in studying spin-thermal effects in metal/magnetic ferromagnet hybrid structures [3, 4]. The spin Seebeck effect (SSE) in such structures can be realized by exciting a system of localized spins. In this case, inelastic scattering of the spin-polarized electrons on localized moments located at the (N/F) interface leads to a non-equilibrium distribution of magnons.

Among other ways of observing SSE there are resonant methods of influencing on the conduction electron subsystem to disturb the magnetic spin localized subsystem. For example, the magnetic subsystem, when disturbed by an alternating magnetic field under ferromagnetic resonance conditions, causes the effect of electron-spin pumping or creates an electron-spin current. Using of the given method allows one to generate

the electron-spin current without transporting the spin-polarized charge carriers through the interface, thereby avoiding the problem of conductivity mismatch (the mismatch problem) [5, 6, 7]. However, the method above is not applicable to the SSE because of a feedback required - the electron subsystem should transfer the angular momentum to the localized magnetic moments subsystem. As it will be seen below, the spin-orbital interaction realizes the desired "resonance" scenario that results in resonantly exciting spin-wave current.

The spin orbit interaction (SOI) couples the kinetic (translational) and spin subsystems of conduction electrons. Thus, the SOI is one of the possible channels to act on one of the subsystems via another, for example, on the spin subsystem of conduction electrons via the kinetic subsystem and vice versa. Due to the translational and spin motion chaining, the quantum transitions cannot be conventionally divided into pure configurational (orbital) and pure spin ones. We can only talk about either predominantly configurational or predominantly spin transitions. However, this circumstance significantly changes the conditions for the excitation of different transitions. Namely, the electrical component of an electromagnetic field initiates the spin transitions, and the magnetic component the orbital ones. The spin orbit interaction gives rise to the resonant electron transitions at frequencies being linear combinations of the cyclotron and Zeeman frequencies. Besides, such tran-

sitions can exist at the antinode of both electric and magnetic fields. Such resonance is known as the Rashba combined resonance [8, 9, 10]. The powers absorbed by the electrons under saturation of the combined resonance (CR) and the paramagnetic resonance (PR) at the antinode of the electric field differ dramatically in magnitude.

Apparently, by resonantly exciting a spin subsystem in the semiconductor/magnetic insulator structures under conditions at hand, we will succeed in implementing the SSE, where the excitation of the spin-wave current bears a resonance nature.

The solution of the problem reduces to constructing a set of macroscopic transfer equations for the conduction electron spin subsystem $\langle \dot{s}^z \rangle^t$ and localized spin subsystem $\langle \dot{S}^z \rangle^t$ of the insulator:

$$\dot{A} = (i\hbar)^{-1} [A, H], \quad \langle A \rangle^t = Tr(\rho(t) A), \quad (1)$$

where H is the total Hamiltonian of the system considered: a semiconductor, a magnetic insulator, and a lattice. $\rho(t)$ is the non-equilibrium statistical operator (NSO) [11].

First, let us take a look at how the electron subsystem evolves. The smallness of the spin-orbit interaction underlies the theoretical description of combined resonance transitions and the calculation of the power absorbed by conduction electrons in metals or semiconductors [8]. This allows one to build a "new" effective Hamiltonian by canonically transforming the initial Hamiltonian [10]. The result of the canonical transformation is to eliminate the interaction between the spin and kinetic degrees of freedom of electrons in the linear spin-orbit interaction approximation. In this case, the interaction between the electron system and the electromagnetic field is also renormalized and determines the resonant energy absorption. Suppose the canonical transformation of the Hamiltonian to be already made and let the renormalized interaction with the alternating electric field have the form [10]

$$\begin{aligned} \bar{H}_{ef}(t) &= [\mathbf{r}, T(p)] e \mathbf{E}(t), \\ T(p) &= R \sum \frac{T^{\alpha_1, \dots, \alpha_s; \beta}}{\hbar \Omega_{\alpha_1, \dots, \alpha_s; \gamma}} \end{aligned} \quad (2)$$

where e is the charge of an electron. $T(p)$ is the operator of the canonical transformation; $\Omega_{\alpha_1, \dots, \alpha_s; \gamma}$ is a linear combination of the cyclotron ω_0 , and the Zeeman ω_s frequencies of electrons, this combination depends on the particular structure of the operator $T^{\alpha_1, \dots, \alpha_s; \gamma} = s_j^{\alpha_1} \dots s_j^{\alpha_s} p_j^{\gamma}$ (s_j^{α} , p_j^{γ} are the components of a spin and a momentum of the j -th electron) and the spin-orbital interaction constant R .

Note that the resonance at the Zeeman frequency corresponds to the transformation operator $T(p)$ linear in momentum. For simplicity, the electric dipole resonance is assumed to be realized in the considered system under the electric field of the electromagnetic wave. Macroscopic equations for the density of the spin magnetization of conduction electrons $\delta m^z(\mathbf{x}, t) = g_s \mu_0 \delta \langle s^z(\mathbf{x}) \rangle^t$ can be constructed by averaging the operator equation by the NSO $\rho(t)$ [11]

$$\begin{aligned} \frac{\partial}{\partial t} \delta m^z(\mathbf{x}, t) &= -\nabla \langle I_{H_s}(\mathbf{x}) \rangle^t + \\ &+ \langle \dot{H}_{s(sm)}(\mathbf{x}) \rangle^t + \langle \dot{H}_{s(eF)}(\mathbf{x}, t) \rangle^t. \end{aligned} \quad (3)$$

Equation. (3) describes the change in the spin magnetization density of the electronic subsystem due to the following processes: diffusion (the first summands in the right-hand sides of the equation), relaxation as a result of the exchange interaction between electrons with localized moments at the interface (second summand), and energy absorption from an external electrical field by the spin subsystem of conduction electrons $\langle \dot{H}_{s(eF)}(\mathbf{x}, t) \rangle^t \equiv Q_s(\mathbf{x}, t)$.

According to [4] an expression for the average power absorbed by the spin subsystem of conduction electrons under electric dipole resonance can be written as

$$Q_s = \beta \omega_s^2 R^2 \sum_{\mathbf{q}, \omega} \frac{|E^-(\omega)|^2 \omega^2 \chi_s \Gamma(\mathbf{q}, \omega)}{(\omega - \omega_s)^2 + \Gamma^2(\mathbf{q}, \omega)}, \quad (4)$$

where $\beta^{-1} = k_b T$ (k_b is the Boltzman const, T - is the temperature), $\chi_s = (s^+(\mathbf{q}), s^-(\mathbf{-q}))_0$.

$$(A, B)_0 = \int_0^1 d\lambda Sp\{A \rho_0^\lambda \Delta B \rho_0^{1-\lambda}\}$$

and $\Delta \langle A \rangle^t = \langle A \rangle^t - \langle A \rangle_0$. ρ_0 is the equilibrium statistical operator.

$$\Gamma(\mathbf{q}, \omega) = \nu(\mathbf{q}, \omega) + q^\alpha q^\gamma D_{\alpha, \gamma}^\pm(\mathbf{q}, \omega).$$

Here $\nu(\mathbf{q}, \omega) \equiv \nu_s$ is the known formula for the frequency of the transverse electron spin relaxation; it defines, for example, the line width of paramagnetic resonance [12]. $D_{\alpha, \gamma}^\pm(\mathbf{q}, \omega)$ is the diffusion tensor for the transverse spin magnetization components

$$\begin{aligned} \nu(\mathbf{q}, \omega) &= \chi_s^{-1}(\mathbf{q}) \times \\ &\times Re \int_{-\infty}^0 dt_1 e^{(\epsilon - i\omega)t_1} (\dot{s}_{(em)}^+(\mathbf{q}), \dot{s}_{(em)}^-(\mathbf{-q}, t_1))_0, \end{aligned}$$

$$D_{\alpha,\gamma}^{\pm}(\mathbf{q}, \omega) = \chi_s^{-1}(\mathbf{q}) \times \\ \times \text{Re} \int_{-\infty}^0 dt_1 e^{(\epsilon - i\omega)t_1} (I_{s+}^{\alpha}(\mathbf{q}), I_{s-}^{\gamma}(-\mathbf{q}, t_1))_0.$$

Macroscopic equations for the spin magnetization density of the localized spins $\delta M^z(\mathbf{x}, t) = g_m \mu_0 \delta \langle S^z(\mathbf{x}) \rangle^t$ has a similar structure

$$\frac{\partial}{\partial t} \delta M^z(\mathbf{x}, t) = -\nabla \langle I_{H_m}(\mathbf{x}) \rangle^t + \\ \langle \dot{H}_{m(sm)}(\mathbf{x}) \rangle^t + \langle \dot{H}_{m(pm)}(\mathbf{x}) \rangle^t. \quad (5)$$

The first summand in the right-hand side of the equation governs diffusion flux, the second and third ones describe relaxation processes as a result of the exchange magnon-electron interaction at the interface, and their relaxation by phonons. Expressions for these coefficients are:

$$\langle I_{H_m}^{\alpha}(\mathbf{x}, t) \rangle^t = \\ = \int d\mathbf{x}' \int_{-\infty}^0 dt_1 e^{\epsilon t_1} \{ (I_{H_m}^{\alpha}(\mathbf{x}), I_{H_m}^{\lambda}(\mathbf{x}', t_1) \nabla \beta_m^{\lambda}(\mathbf{x}', T)) \\ \langle \dot{H}_{i(jn)}(\mathbf{x}, t) \rangle^t = \\ = \int d\mathbf{x}' \int_{-\infty}^0 dt_1 e^{\epsilon t_1} (\dot{H}_{i(jn)}(\mathbf{x}), \dot{H}_{i(jn)}(\mathbf{x}', t_1)) \delta \beta_j(\mathbf{x}', T), \\ i, j = s, m, n = m, p, \quad T = t + t_1$$

The Eqs. (3), (5) and the kinetic coefficients $\langle I_{H_m}(\mathbf{x}, t) \rangle^t$, $\langle \dot{H}_{i(jn)}(\mathbf{x}, t) \rangle^t$ solve the problem of macroscopic description of non-equilibrium spin subsystems in terms of average magnetization densities.

The analysis of the set of Eqs. (3), (5) shows that, for the stationary state, the spin current in the magnetic insulator characterizes the deviation of magnetization from equilibrium and can be expressed by:

$$\delta M^z(\omega) \simeq -\beta \left(\frac{R \omega_m}{\omega_s \nu_{(mp)}} \right)^2 \times \\ \times \sum_{\omega} |E(\omega)|^2 \frac{\omega^2 \chi_s \nu_s}{(\omega - \omega_s)^2 + \nu_s^2}, \quad (6)$$

where $\nu_{(mp)}$ is the frequency of magnon-phonon relaxation and depends on frequency of an external field.

In the effective parameter approximation, when each of the subsystem considered (conduction electrons, magnons, and phonons) is characterized by its effective temperature, it can be concluded that the resonance

excitation of the conduction electron spin subsystem in the metal (semiconductor)/ferromagnetic insulator hybrid structure provides the resonant generation of the spin-wave current in the magnetic subsystem of localized spins.

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