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Bulk magnon spin current theory for the longitudinal spin Seebeck effect

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ABSTRACT

The longitudinal spin Seebeck effect (LSSE) consists in the generation of a spin current parallel to a temperature gradient applied across the thickness of a bilayer made of a ferromagnetic insulator (FMI), such as yttrium iron garnet (YIG), and a metallic layer (ML) with strong spin orbit coupling, such as platinum. The LSSE is usually detected by a DC voltage generated along the ML due to the conversion of the spin current into a charge current perpendicular to the static magnetic field by means of the inverse spin Hall effect. Here we present a model for the LSSE that relies on the bulk magnon spin current created by the temperature gradient across the thickness of the FMI. We show that the spin current pumped into the metallic layer by the magnon accumulation in the FMI provides continuity of the spin current at the FMI/ML interface and is essential for the existence of the LSSE. The results of the theory are in good agreement with experimental LSSE data in YIG/Pt bilayers on the variation of the DC voltage with the sample temperature, with the FMI layer thickness and with the intensity of high magnetic fields.

1. Introduction

The spin Seebeck effect (SSE) refers to the generation of a spin current in ferromagnetic or ferrimagnetic (FM) materials by a temperature gradient, and is the analog of the ancient thermoelectric Seebeck effect whereby a charge current is created by a temperature gradient in a metal [1–4]. Discovered in 2008 by Uchida and co-workers [5], the SSE was soon observed in a variety of materials and structures [1–12], arousing the field of spintronics and giving origin to the area of spin caloritronics. The SSE is usually detected by the voltage created in a metallic layer (ML) attached to the FM layer as a result of the conversion of the spin current into a charge current by means of the inverse spin Hall effect (ISHE). The FM material can be a metal, semiconductor, or an insulator, while the ML is made of a paramagnetic metallic material with strong spin orbit coupling, such as Pt or Ta, or a FM material such as permalloy [13], or an antiferromagnetic metal such as IrMn [14,15]. Other ways to observe the SSE involve the action of torques created by spin currents on the spin dynamics [16–19]. There is currently intense effort to understand in detail the origins of the SSE and to find new materials and structures for possible applications, such as in thermopower conversion devices.

Depending on the experimental arrangement, the spin current generated by the SSE can be perpendicular or parallel to the temperature gradient, characterizing the so-called transverse or longitudinal configurations respectively [1–4]. While the transverse SSE can be observed in both metallic and insulating magnetic materials, the longitudinal spin Seebeck effect (LSSE) is observed unambiguously only in insulators because they are free from the anomalous Nernst effect [1–4,8,9,20,21]. The longitudinal configuration has proved to be more interesting for scientific research and for applications, and most experiments on the LSSE have been done with the low magnetic loss ferrimagnetic insulator (FMI) yttrium iron garnet ($Y_3Fe_5O_{12}$ or YIG) which has been the reference material for the study of a variety of magnonic phenomena, linear [22] and nonlinear [23]. There is consensus that the LSSE consists of two steps: (1) a spin current created by the action of a thermal gradient in the FMI/ML structure is pumped into the ML; (2) the spin current in the ML is converted into a charge current by means of the inverse spin Hall effect (ISHE) [24–27] producing the electric voltage. However, the origin of the spin current is controversial. Some authors argue that the spin current results from the temperature difference between the FMI and the metallic layer which produces a thermal interfacial spin pumping [1,2,28–33]. On the other hand, according to our earlier proposal [34], the LSSE originates in the bulk magnon thermal flow across the thickness of the FMI film created by the temperature gradient. This mechanism relies on the magnon spin current generated in the bulk of the FMI film, not at the interface, but it requires the contact with a ML to provide continuity for the spin flow. In this

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paper we show that the bulk magnon spin current model, with an improvement in the original formulation, explains the recent measurements of the LSSE at high magnetic fields, as well as the earlier measurements on the temperature and thickness dependences of the LSSE in YIG/Pt bilayers.

2. Bulk magnon spin current model for the LSSE

The bulk magnon spin current model for the LSSE is based on the spin current created by the temperature gradient across the thickness of the FMI/ML bilayer, as illustrated in Fig. 1. The spin current in the FMI is carried by the spin waves, or magnons, with wave vector $\vec{k}$ and energy $\varepsilon_k = \hbar\omega_k$ [35–41]. At the FMI/ML interface the thermal magnons in excess of thermal equilibrium pump a spin current into the ML by means of the spin pumping process [42,43]. The magnon distribution across the thickness can be calculated using the equations of motion subject to the boundary conditions, determined by the continuity of spin current at the interfaces. We choose a coordinate system with the z axis parallel to the magnetic field H applied in the plane, and the y axis perpendicular to the plane, shown in Fig. 1. Denote by n_k the number of magnons with wave number k in the whole volume V of the FMI layer, n_k^0 the number in thermal equilibrium, given by the Bose-Einstein distribution, $n_k^0 = 1/[\exp(\varepsilon_k/k_BT) - 1]$, and $\delta\, n_k(\vec{r}) = n_k(\vec{r}) - n_k^0$ the number in excess of equilibrium. The magnon accumulation $\delta\, n_m(\vec{r})$ is defined as the density of magnons in excess of equilibrium [40,41]

$$\delta\, n_m(\vec{r}) = \frac{1}{(2\pi)^3}\int d^3k [\, n_k(\vec{r}) - n_k^0], \tag{1}$$

and the bulk magnon spin-current density with polarization z is [39–41]

$$\vec{J}_S^{\,z} = \frac{\hbar}{(2\pi)^3}\int d^3k\, \vec{v}_k\, [n_k(\vec{r}) - n_k^0\,], \tag{2}$$

where $\vec{v}_k$ is the k-magnon velocity. The distribution of the magnon number under the influence of a thermal gradient can be calculated with Boltzmann transport equation [44]. In the absence of external forces and in the relaxation approximation, in steady state Boltzmann equation gives

$$n_k(\vec{r}) - n_k^0 = -\tau_k \vec{v}_k\cdot\nabla n_k(\vec{r}), \tag{3}$$

where τ_k is the k-magnon relaxation time. Using Eq. (3) in Eq. (2) one can show that the spin current is the sum of two parts, $\vec{J}_S^{\,z} = \vec{J}_{S\nabla T}^{\,z} + \vec{J}_{S\delta n}^{\,z}$, where

$$\vec{J}_{S\nabla T}^{\,z} = -\frac{\hbar}{(2\pi)^3}\int d^3k\, \tau_k \frac{\partial\, n_k^0}{\partial\, T}\vec{v}_k(\vec{v}_k\cdot\nabla T) \tag{4}$$

is the contribution of the flow (convection) of magnons due to the temperature gradient and

$$\vec{J}_{S\delta n}^{\,z} = -\frac{\hbar}{(2\pi)^3}\int d^3k\, \tau_k\, \vec{v}_k[\vec{v}_k\cdot\nabla\delta\, n_k(\vec{r})] \tag{5}$$

is due to the spatial variation of the magnon accumulation. With the temperature gradient normal to the plane, Eq. (4) gives the spin current in the y-direction

$$J_S^z = -C_S^z\nabla T, \tag{6}$$

$$C_S^z = \frac{\hbar}{(2\pi)^3 T}\int d^3k\, \tau_k v_{ky}^2 \frac{e^x\, x}{(e^x - 1)^2}, \tag{7}$$

where T is the average temperature and $x = \varepsilon_k/k_BT$ is the normalized magnon energy. We consider the magnon and phonon systems to have the same temperature T as demonstrated experimentally [45]. In order to calculate the spin current due to the gradient of the magnon accumulation, one needs to relate the integral in Eq. (5) with the expression in Eq. (1). For this it is necessary to use an approximate solution of Boltzmann equation in the spirit of linear response theory and write the excess magnon number as the sum of the equilibrium distribution plus a small deviation. In the original formulation of the model [34] we used an expansion in terms of $\partial n_k^0/\partial\varepsilon_k$ and obtained a temperature dependence of the LSSE in good agreement with the existing experiments. However, comparison of theory with recent measurements of the LSSE at high magnetic fields [31,46] gave discrepant dependences on the field intensity. The reason is that some integrals involving $\partial n_k^0/\partial\varepsilon_k$ diverge if the magnon dispersion is gapless. In Refs. [34,39,40] this divergence was avoided by considering a gap introduced either by a finite external field or a cut-off in wave number near $k = 0$. It turns out that the LSSE measurements do not show any anomaly at zero-field. So we conclude that the expansion used earlier introduces a spurious dependence on the field. Here we use an improved solution for Boltzmann equation. Consider for the magnon number a small deviation from the equilibrium distribution in the form $n_k(\vec{r}) = n_k^0 + n_k^0[1 + \lambda_k\, g(\vec{r})]$ [44], such that λ_k in lowest order of energy is chosen as to eliminate the singularity at $\varepsilon_k = 0$. This is

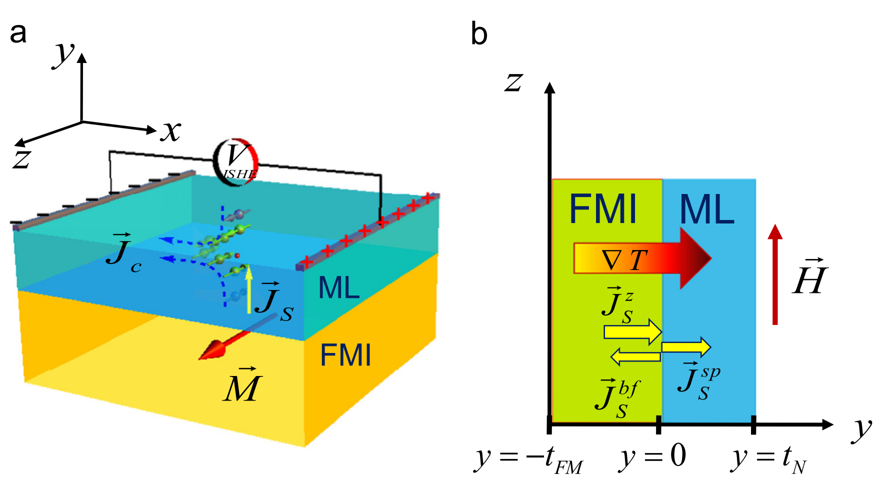

Fig. 1. Ferromagnetic insulator (FMI)/metallic layer (ML) bilayer used to investigate the longitudinal spin Seebeck effect. (a) Illustration of the conversion of spin into charge current by the inverse spin Hall effect in the ML. (b) Coordinate axes used to calculate the spin currents generated by a temperature gradient perpendicular to the plane of the bilayer.