Spin current through a normal-metal/insulating-ferromagnet Junction

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Abstract. We study the spin current across the interface between a normal metal and an insulating ferromagnet in a junction. At the interface, conduction electrons in the normal metal interact with localized moments of the ferromagnet via the sd-type exchange interaction. In the presence of spin accumulation in the normal metal, the spin accumulation decays by spin-flip scattering of conduction electrons at the interface, thereby emitting magnons through the exchange interaction at the interface. Using the linear response theory, we obtain the spin current through the interface, which is proportional to spin accumulation as well as the population of magnons.

Recently, there has been an increased interest in spin-dependent transport in magnetic nanostructures not only in emergence of new phenomena but also in potential application to spintronic devices [1]. Recent experimental and theoretical studies have demonstrated that the spin-polarized carriers injected from a ferromagnet into a nonmagnetic material, such as a normal conducting metal, semiconductor, and superconductor, create nonequilibrium spin accumulation and spin current over the spin diffusion length ranging from nanometer to micrometer scale. Efficient spin injection, spin accumulation, spin transfer, spin detection, conversion between spin and charge currents [2, 3, 4, 5, 6], and spin-Seebeck effect [7] are key factors in realizing new functional spintronic devices [8, 9].

In nonmagnetic and magnetic conductors, charge and spin are carried by electrons. In a metallic ferromagnet, the spin current always flows by application of bias voltage, since the spins of conductive electrons are spontaneously polarized. In nonmagnetic metals, the spin current is created by spin injection from a ferromagnet or by the spin Hall effect. The spin current in nonmagnetic metals is called “pure spin current”, because up-spin and down-spin electrons flow in the opposite directions without accompanying charge current. In this way, conductive materials carry the spin current by conduction electrons.

Insulating ferromagnets have unique properties in that they are electrically inactive with frozen charge degrees of freedom, but magnetically active due to the spin degrees of freedom of localized spins; low-lying excitation is spin wave (magnon) which carries integer spin angular momentum. A basic question arises: in what way the spin current is injected into insulating ferromagnets by exciting magnons? Efficient spin injection into insulating ferromagnets is important for developing new spintronic devices.

In this work, we demonstrate that the spin current flows across the interface between an insulating ferromagnet and a normal metal of accumulated spin bath. The spin-flip scattering
of conduction electrons through the exchange interaction with local moments at the interface, creates a magnon excitation in the ferromagnet. Making use of linear response theory, we obtain an analytical expression for spin current through the interface, which is proportional to the magnitude of spin accumulation as well as the population of magnons.

Let us consider a junction which consists of a normal metal (N) and an insulating ferromagnet (F) as shown in Fig. 1. For simplicity, we assume a uniform spin accumulation in N with splitting of up and down spin chemical potentials, \( \delta \mu_N = \mu^\uparrow - \mu^\downarrow \), which is created by spin injection from other ferromagnets connected to N or by the spin Hall effect in N.

When an electron in N is incident on the interface, the electron is always reflected at the F/N interface, because the electron is not allowed to penetrate into F. At the scattering, there exists a spin-flip process in which an electron spin reverses its direction, thereby emitting or absorbing a magnon in F. The spin-flip scattering accompanied by magnon excitation leads to the transfer of spin angular momentum between the left and right electrodes. When the up-spin chemical potential is higher than the down-spin chemical potential (see Fig. 1), the spin-flip process from up-spin to down spin state dominates over the reversed process, so that the spin current flows from N into F across the F/N interface.

The electron-magnon interaction at the interface may be described by the \( sd \)-type exchange interaction:

\[
H_{sd} = J_{\text{eff}} \sum_{k,k',q} \left[ S_q^{-} c_{k'\uparrow}^\dagger c_{k\downarrow} + S_q^{+} c_{k'\downarrow}^\dagger c_{k\uparrow} + S_q^{z} (c_{k'\uparrow}^\dagger c_{k\downarrow} - c_{k'\downarrow}^\dagger c_{k\uparrow}) \right],
\]

where \( c_{k\sigma} \) is the annihilation operator of an incident electron with momentum \( k \) and spin \( \sigma \) in N, \( c_{k'\sigma'}^\dagger \) is the creation operator of a reflected electron with momentum \( k' \) and spin \( \sigma' \), \( S_q^{\pm} = S_q^{x} \pm i S_q^{y} \), \( S_q = (S_q^{x}, S_q^{y}, S_q^{z}) \) is the localized spin operator with momentum \( q \) in F, and \( J_{\text{eff}} \) is the effective exchange interaction. We assume a rough interface in which the transverse component of momentum is not conserved (incoherent electron scattering), so that the summation over the wave vectors \( k, k', \) and \( q \) in Eq. (1) is made independently.

The spin current operator \( J_s \) across the junction is calculated by \( J_s = (1/2)(d/dt)(N_\uparrow - N_\downarrow) \), where \( N_\sigma = \sum_k c_{k\sigma}^\dagger c_{k\sigma} \) is the spin-dependent number operator. Using the Heisenberg equation of motion, the spin current operator is expressed as

\[
\hat{J}_s = \frac{i}{\hbar} J_{\text{eff}} \sum_{k,k',q} S_q^{-} c_{k'\uparrow}^\dagger c_{k\downarrow} - \frac{i}{\hbar} J_{\text{eff}} \sum_{k',p} S_q^{+} c_{k'\downarrow}^\dagger c_{k\uparrow}.
\]
Using the linear-response theory, we can calculate the spin current $J_s$ across the interface

$$J_s = -\frac{i}{\hbar} \int_{-\infty}^{t} dt' \left\langle \left[ \mathcal{J}_s(t), H_{sd}(t') \right] \right\rangle = \frac{4}{\pi^2} J_{sd}^2 \text{Im} \left[ U_{\text{ret}}(\delta \mu) \right],$$

with the Fourier component $U_{\text{ret}}(\delta \mu)$ of the retarded correlation function $U_{\text{ret}}(t)$ defined as [10]

$$U_{\text{ret}}(\delta \mu) = \int_{-\infty}^{\infty} dt e^{i\delta \mu t} U_{\text{ret}}(t), \quad U_{\text{ret}}(t) = -i\Theta(t) \left\langle \left[ A(t), A^\dagger(0) \right] \right\rangle,$$

where $\delta \mu = \mu_\uparrow - \mu_\downarrow$ corresponds to the spin voltage, and $A$ and $A^\dagger$ are the operators defined by

$$A(t) = \sum_{k,k',q} S_q^-(t) c_{k',\uparrow}^\dagger(t) c_{k,\downarrow}(t), \quad A^\dagger(t) = \sum_{k,k',q} S_q^+(t) c_{k',\downarrow}^\dagger(t) c_{k,\uparrow}(t).$$

Using the relation between the Matsubara and the retarded functions [10], we can calculate the spin current by evaluating the imaginary-time correlation function

$$U(i\Omega_q) = -\int_{0}^{\beta} d\tau e^{i\Omega_q \tau} \left\langle \left[ A(\tau), A^\dagger(0) \right] \right\rangle = \sum_{k,k',q} \int_{0}^{\beta} d\tau e^{i\Omega_q \tau} \chi_q^+(\tau) G_{k\uparrow}(\tau) G_{k'\downarrow}(\tau),$$

where $\beta = 1/(k_B T)$, $\Omega_q$ is a bosonic frequency (later the analytical continuation $i\Omega_q \to \delta \mu + i\delta$ is made), $G_{k\sigma}(\tau) = -\langle T_\tau [c_{k\sigma}(\tau) c_{k\sigma}^\dagger(0)] \rangle$ and $\chi_q^+(\tau) = -\langle T_\tau [S_q^- c_{k\uparrow}^\dagger c_{k\downarrow}] \rangle$ are the electron and spin Green’s functions,

$$G_{k\sigma}(\tau) = k_B T \sum_{\omega_n} e^{-i\omega_n \tau} \frac{1}{i\omega_n - \xi_k}, \quad \chi_q^+(\tau) = k_B T \sum_{\nu_m} e^{-i\nu_m \tau} \frac{1}{-i\nu_m - \omega_q},$$

where $\xi_k$ is the one-electron energy, $\omega_q$ is the magnon energy, $\omega_n = (2n + 1)\pi k_B T$, and $\nu_m = 2m\pi k_B T$.

Figure 2 shows the Feynman diagrams for calculating the spin current flowing in the left and right directions across the interface. At the interface, magnons are emitted or absorbed by spin-flip reflection of electrons at the interface. Summing over the frequencies, $\omega_n$ and $\nu_m$, and making an analytic continuation $i\Omega_q \to \delta \mu + i\delta$, we have

$$J_s(\delta \mu) = -\frac{4\pi}{\hbar} \langle S_z \rangle J_{sd}^2 N(0) \sum_{k,q} [f(\xi_k + \omega_q - \delta \mu) - f(\xi_k)] \left[ n(\omega_q - \delta \mu) - n(\omega_q) \right]$$

$$+ \frac{4\pi}{\hbar} \langle S_z \rangle J_{sd}^2 N(0) \sum_{k,q} [f(\xi_k + \omega_q + \delta \mu) - f(\xi_k)] \left[ n(\omega_q + \delta \mu) - n(\omega_q) \right],$$

where $N(0)$ is the density of states at the Fermi level, $f(\xi_k)$ is the Fermi distribution function and $n(\omega_q)$ is the Bose distribution function. Note that $J_s$ vanishes for $\delta \mu \to 0$ as expected. Since $(\omega_q \pm \delta \mu)$ is much smaller than the Fermi energy, Eq. (8) becomes

$$J_s = 8\pi^2 \frac{e}{\hbar} \langle S_z \rangle [J_{sd} N(0)]^2 \left[ T \frac{\partial}{\partial T} N_m(T) \right] \delta \mu,$$

where $N_m(T) = \sum_q [e^{\beta \omega_q} - 1]^{-1}$ is the population of magnons and $\beta = 1/k_B T$. Equation (9) shows that the spin current is proportional to the spin accumulation $\delta \mu$ and the population of magnons; for a parabolic dispersion without gap, $J_s$ has a temperature dependence of $T^{3/2}$. 
To understand how the spin current depends on spin accumulation and magnon energies, we examine a simple model in which magnons have the same energy $\omega_0$, for which Eq. (8) becomes

$$J_s = \frac{4\pi}{\hbar} \langle S_z \rangle |J_{\text{eff}} N(0)|^2 (\omega_0 - \delta \mu) \left[ \frac{1}{e^{\beta(\omega_0-\delta \mu)}-1} - \frac{1}{e^{\beta \omega_0}-1} \right].$$

(10)

Figure 3 shows the normalized spin current $J_s/J_s^0$ versus spin accumulation $\delta \mu$ for several values of $\delta \mu/\omega_0$, where $J_s^0 = (4\pi/\hbar) \langle S_z \rangle |J_{\text{eff}} N(0)|^2 \omega_0$. For $\omega_0/k_B T \gg 1$, $J_s$ has a gap for $\delta \mu < \omega_0$ and increases above $\omega_0$. As $\omega_0/k_B T$ increases, $J_s$ rapidly increases in a linear fashion as $J_s/J_s^0 \approx (k_B T/\omega_0)(\delta \mu/\omega_0)$.

In summary, we studied the spin current across the interface between an insulating ferromagnet and a normal metal with spin accumulation. Due to the exchange interaction of conduction electrons with localized moments at the interface, the spin current is able to flow by converting spin accumulation into magnons. The spin current predicted in this paper is proportional to spin accumulation as well as population of magnons. Spin accumulation plays a role of spin voltage for generating magnon in insulating ferromagnets.

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