Spin Current Generation in One – Dimension Spin – Chain Model of Insulating Magnetic Interface

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Abstract. In a system of a thin ferromagnetic layer sandwiched by non-magnetic metals, the precession of magnetization of the ferromagnetic layer has been shown to generate spin current in the adjacent non-magnetic metals. The spin current arises from the spin-dependent scattering that is originated by the exchange interaction between the magnetic moment and the spin of adjacent normal metal’s electron. While the theory was originally studied in magnetic multilayer that consists of a thin ferromagnet sandwiched by non-magnetic materials, to be able to describe a more realistic ferromagnetic layer, we need to study how magnetic moments far from the interface can influence the spin current generation. We use a simple model one dimension ferromagnetic spin chain to show the criteria in which the collective movements of the spin moments can enhance the spin current generation.

Keywords: spin pumping, spin current, spin chain

1. Introduction
While conventional electronics focuses on charges degree of freedom, field of study of spintronics also includes the spin degree of freedom. As the size of electronic devices reduces to nanosize, spin properties become important, since the electron scattering in this scale still conserve its spin angular momentum. Because of the conservation of the spin angular momentum, we need to consider spin current when studying the electronics transport of nanoscale materials [1,2,3].

Spin current can be generated by spin pumping effect. In a bilayer of ferromagnet and non-magnetic metal, movement of the magnetization of the ferromagnet pumps spin current into the adjacent non-magnetic metal. The pumped spin current is characterized by spin-mixing conductance parameter [4,5]. The spin-mixing conductance \( g_{↑↓} = g_r + ig_i \) is complex-valued, with \( g_i \ll g_r \). Spin current is a tensor, which has current direction and polarization direction. In the case of spin pumping, the current direction is from ferromagnet to non-magnetic metal, while the polarization direction \( J_s \) is characterized by spin-mixing conductance parameter.

\[
J_s = g_r m \times \dot{m} - g_i \dot{m}
\]

Here \( m \) is the normalized magnetization vector and spin-mixing conductance \( g_{↑↓} = g_r + ig_i \) is complex-valued, with \( g_i \ll g_r \).
Although the theory was developed for ferromagnetic metal, spin pumping experiment showed that ferromagnetic insulators also generate spin current with similar magnitude [6,7]. The theory was originally studied in magnetic multilayer that consists of a thin ferromagnet sandwiched by non-magnetic materials. When the ferromagnet is thin enough, its magnetic moments can be considered as a uniform (coherently moving) magnetic moments [4,8]. We determine the criteria in which the coherent magnetic moments approximation held. The spin current transport in the bulk and the interface of one-dimension spin chain, the simplest case ferromagnet with one dimensional symmetry, sandwiched by non-magnetic metal, are discussed in section 2 and 3, respectively.

2. Spin current in insulating one dimensional spin chain

One dimensional ferromagnet can be modeled by an array of spins. The exchange interaction of the spin chain can be represented in the following Hamiltonian.

\[ H = -J \sum S_n \cdot S_{n+1}. \]  

(2)

where \( J \) is the exchange constant and \( S_n \) is the \( n \)-th spin, which interact only with the nearest spins \( S_{n-1} \) and \( S_{n+1} \). The collective movement of this spin chain is characterized by the magnon dispersion relation

\[ \hbar \omega = 2JS(1 - \cos k \alpha) \]  

(3)

where \( \alpha \) is the distance between each spin. \( \hbar \omega \) and \( k \) are the energy and wave number that characterized the collective movement of the spin chain. The magnon dispersion relation is illustrated in Fig 1.

The collective moment of the spin magnetic moment, \( i.e. \) magnon, generates a magnonic (spin wave) spin current in the bulk of the spin chain. The polarization of the magnonic spin current that flow in \( x \) direction (see Fig 2) is

\[ J_s = M_s J a m \times \frac{\partial m}{\partial x} \]  

(4)

where \( M_s \) is the saturated magnetization [9,10]. In the next section we will determine the boundary condition that should be satisfied by this magnonic spin current.

![Figure 1](image1.png)  
**Figure 1.** Energy and wave number that characterized the collective movement of the magnetic moments in the spin chain follow the magnon dispersion relation.

![Figure 2](image2.png)  
**Figure 2.** Collective movement of spin magnetic moments carry magnonic spin current in the bulk of the ferromagnetic insulator.
3. **Boundary condition of the spin current at interface with non-magnetic metal**

The spin current generated at the non-magnetic metal immediate to the interface with ferromagnetic insulator is characterized by the spin-mixing conductance. For $g_i \ll g_r$, the spin polarization is

$$J_s = g_r m \times \dot{m}$$

(5)

The origin of spin mixing conductance is the spin-dependent scattering due to the exchange interaction between spins of the conduction electron and the spin of the ferromagnetic insulator [9,10].

![Figure 3](image)

**Figure 3.** A bilayer of ferromagnetic insulator and non-magnetic metal. Spin current transport across the interface of ferromagnetic insulator and non-magnetic metal. When the scattering at the interface conserves spin, there should be spin current continuity across the interface.

Assuming the conservation of spin angular momentum in the interface scatterings, there should be a spin current continuity across the interface, which suggested the following boundary condition [10]

$$M_s J_a \frac{\partial m}{\partial x} + g_r \dot{m} = 0$$

(6)

$$\omega = \frac{M_s J_a}{g_r} k$$

Eq (6) suggest the following criteria for combination of $\omega$ and $k$ that satisfy the boundary condition

Drawing Eq. (6) into the magnon dispersion relation, we arrive at the minimum value of the spin mixing conductance

$$g_0 \approx 0.68 \frac{\hbar M_s}{S}$$

(7)

in which the coherent-magnetic-moments model is a good approximation. It should be noted here that the frequency of this coherent movement in our case is zero because we neglected the influence of applied magnetic field and anisotropic fields. If these fields are included, the coherent frequency will correspond to the precession frequency due to these fields.
Figure 4. Red line represents the critical value of spin mixing conductance. A coherent magnetic moments approximation is a good approximation when the spin mixing conductance is small than this critical value (green line). However, other modes of collective movements, $k$ and $\omega$ that satisfy Eqs. (3) and (6), should be taken into account when the spin mixing conductance is larger than the critical value (blue line).

4. Conclusion

We discussed the distribution of spin current in the bulk of the ferromagnetic insulator and its interface with non-magnetic metal. In the bulk, the spin current carried by the collective movement of the spin magnetic moment, i.e. magnon. On the other hand, in the metal side, spin current is carried by moving charges (see Fig 3). The spin pumping effect transfers the spin angular momentum across the interface and transfer the spin current from the ferromagnetic insulator to the non-magnetic metal.

We found the critical value of the spin mixing conductance, in which a uniform magnetic moment is a good approximation for treating the spin pumping effect from magnetic insulator to non-magnetic metal. It imply that when the spin mixing conductance is larger than the critical value, other modes, $k$ and $\omega$ that satisfy Eqs. (3) and (6), contributes to the spin current transfer. While we discuss the simplest model of one-dimension ferromagnetic insulator, the result can be generalized to a more realistic model. Furthermore, by parameterizing external and anisotropic fields, the discussion can be extended to a more general case.
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