Magnon Contribution on Pure Spin Current Generation in Half-Metal

Adam B. Cahaya and M. A. Majidi*

Department of Physics, Faculty of Mathematics and Natural Sciences Universitas Indonesia, Kampus UI Depok, Depok 16424, Indonesia

*Corresponding author: aziz.majidi@sci.ui.ac.id

Abstract. Half-metal is a class of the metallic ferromagnet having a 100% spin polarization. The conduction electrons of half-metals can only carry electrons with a particular spin orientation. Because of this, the current generation of half-metal is expected to be governed only by the particular conducting spin. However, the contribution of the opposite spin, on which the half-metal acts as an insulator, is often neglected. Here we theoretically study the contribution of this insulating spin on the spin transport in the half-metal, in comparison with the conducting spin. We found that the collective dynamic of the insulating spin is responsible for magnonic transport that in turns influence the spin current generation in the half-metal.

Keywords: Half-metal, magnon, thermoelectric, metallic ferromagnet, spin polarization

1. Introduction

Started from the discovery of giant magnetoresistance (GMR) effect, the study of the spin degree of freedom has led to many applications in magnetic recording technology [1,2]. The study of the spin degree of freedom in electronic transport has led to the development of the spin-electronics or spintronics [3]. As a material with strong spin-dependent properties, ferromagnetic materials are used widely in spintronics. In metallic ferromagnets, the electric current is accompanied by a spin current that carries angular momentum. Unlike electric current, which is a vector, a spin current is a tensor that can be characterized with current and polarization vectors that represent the direction of its movement and its angular momentum direction, respectively [4].

Among classes of magnetic material, half-metal has a very large spin polarization [5]. A half-metallic material is characterized with a vanishing density of states at Fermi level for electrons with one spin orientation. As a consequent, half-metallic material acts as a conductor only to electrons with the opposite spin orientation [6]. The theoretical prediction has shown that Heusler alloys and half-Heusler alloys have half-metallic band structures [7,8].

In term of electric and spin currents, the spin polarization of half-metal means that electric current on a half-metallic bulk is accompanied by an equal amount of spin current that has polarization parallel to the direction of the conducted spin [9]. However, a recent experiment showed that a pure spin current can be transported by a half-metal without any electric currents [10]. From the point of view of spin-
dependent electronic transport, this pure current transport is impossible. A possible physical effect that is responsible for this phenomenon is the contribution of the spin of which half-metal acts as an insulator.

In this manuscript, we theoretically analyze the spin currents generations in the half-metal. In Sec. 2, we describe the theoretical model of the spin current generation in half-metal, focusing on each contribution of the conducting and insulating spins. In Sec. 3 we discuss our results in terms of the coupling of the spin and heat current. Finally, Sec. 4 concludes our results on spin current generation in half-metal that can be useful for applications beyond thermoelectric devices.

2. Theoretical Model
Looking at the value of the spin-dependent density of states at Fermi level, the spins of the half-metal is categorized as a conducting spin and an isolating spin. The relation of the conducting spin and insulating spin is best illustrated by the Slater-Pauling rule of half-metals, which stated that the magnetic moment \( M \) of a half-metal can be written as

\[
M = (N_p - 2n_i)\mu_B,
\]

where \( \mu_B \) is Bohr magneton, \( N_p \) is valence electron number, \( n_i \) is number of electrons in minority states [8]. This Slater-Pauling rule shows that the spin flip scattering in the half-metal are limited and each spins are independent. The conducting spin acts as the valence electron in Eq. (1). On the other hand, the isolating spin corresponds to the minority states.

While this Slater-Pauling rule are based on half metallic Heusler-alloy, the arguments are true for general half metal. In the following subsections, we describe the spin current generation mechanism of the conducting spin and isolating spin.

2.1. Spin current generation by the conducting spin
In a two-current model of majority and minority spins, transport properties of a metallic ferromagnet, the electric \( j_e \), spin \( j_s \) current density vectors can be defined as follows.

\[
\begin{pmatrix}
  j_{e, s}
\end{pmatrix} = \begin{pmatrix}
  j_1 \pm j_1
\end{pmatrix}
\]

Here the polarization of the spin current is parallel to the up spin direction. In a metallic ferromagnet, the relations of spin-dependent current densities \( j_{1, \uparrow} \), heat current density \( j_q \) and their driving forces can be summarized in the following matrix relation [11]. The driving forces depend on temperature gradient \( \nabla T \) and spin-dependent voltages \( V_{\uparrow, \downarrow} \)

\[
\begin{pmatrix}
  j_e \\
  j_s
\end{pmatrix} = -\sigma \begin{pmatrix}
  1 & P & ST \\
  P & 1 & P^{ST} \\
  STP^{ST} & \kappa T / \sigma & \nabla V_{\downarrow} / 2
\end{pmatrix} \begin{pmatrix}
  \nabla V_e / 2 \\
  \nabla T / T
\end{pmatrix}
\]

Where \( \sigma \) is electric conductivity, \( \kappa \) is heat conductivity, \( S \) is the Seebeck coefficient \( V = (V_1 + V_2) / 2 \) and \( V_e = V_1 - V_2 \) are the electric voltage and spin accumulation, respectively. Here \( P \) is the spin polarization of conductivity

\[
P = \frac{\sigma_{\uparrow} - \sigma_{\downarrow}}{\sigma_{\uparrow} + \sigma_{\downarrow}}
\]

where \( \sigma_{\uparrow, \downarrow} \) is the spin-dependent conductivity and

\[
P' = \frac{\sigma_{\uparrow} S_{\uparrow} - \sigma_{\downarrow} S_{\downarrow}}{\sigma_{\uparrow} S_{\uparrow} + \sigma_{\downarrow} S_{\downarrow}}
\]

for ferromagnets that have spin dependent Seebeck coefficients \( S_{\uparrow, \downarrow} \) [9,11]. From Eq. (2), we can set the boundary condition of the spin current generation by setting \( j_e^* = 0 \).

\[
\begin{pmatrix}
  j_e \\
  j_q
\end{pmatrix} = -\sigma \begin{pmatrix}
  1 - P^2 & (P' - P)ST \\
  (P' - P)ST & \kappa T / \sigma
\end{pmatrix} \begin{pmatrix}
  \nabla V_e / 2 \\
  \nabla T / T
\end{pmatrix}
\]
and derive the condition for a pure spin current generation to be
\[
P' \neq P. \tag{7}
\]
In this case, Eq (7) can be fulfilled only when \( \sigma_\uparrow \neq 0 \) or \( \sigma_\downarrow S_\downarrow \neq 0 \). Since the definition of half metal is the vanishing of the density of state of one of the conduction spin band, half metal that fulfilled Eq. (7) is still possible.

2.2. Magnonic spin current generation by the insulating spin
In the case of the insulating spin, because of their vanishing density of state, each of this spin did not move. However, microscopically each of these spins is precessing coherently. This coherent precession carries spin angular momentum which can be written in the following spin current tensor, which can be analogously taken from the magnonic spin current definition in Ref. [12]
\[
\vec{j}_m = -\varepsilon_{abc}A_m b \nabla c,
\tag{8}
\]
where constant \( A \) depends on the coupling strength of the spins, \( m_b \) is the \( b \)-component of the normalized magnetization, the subscript \( a \) of the spin current indicates the polarization direction and \( \varepsilon_{abc} \) is the Levi-Civita notation that indicates cross product. The current direction of the spin current is determined by the gradient.

\[\text{Figure 1}\] The magnetism of a half-metal comes not only from the electron with conducting spin (green arrow) but also from the opposite insulating spin (red arrows). The insulating spin moves collectively to form a magnonic transport that carries spin and heat currents.

The magnonic spin current under a temperature gradient \( \nabla T = \Delta T/L \) and spin accumulation gradient \( \nabla V_s^a = \Delta V_s^a /L \) gradient can be written in the following form.
\[
\vec{j}_s = -\sigma_s (\nabla V_s^a + S_s \nabla T), \tag{9}
\]
where the polarization of the spin current is now parallel to the averaged direction of the magnetization and the coefficient \( \sigma_s \) and \( S_s \) can be determined by taking account the contribution of all wavevector mode of the magnonic spin current
\[
\vec{j}_m = -\varepsilon_{abc} A_m b c \sum i \vec{k} n(z, \vec{k}) \tag{10}
\]
where \( n(z, \vec{k}) \) is the magnon-distribution function defined in Ref. [13]
\[
n(0, \vec{k}) = \begin{cases} 
\frac{1}{e^{(\beta \omega - \vec{m} \cdot \vec{V}_s)/k_B T} - 1} & \text{for } k_z > 0 \\
0 & \text{for } k_z < 0 
\end{cases}
\tag{11}
\]
and
\[
n(L, \vec{k}) = \begin{cases} 
\frac{1}{e^{(\beta \omega - \vec{m} \cdot (V_s + \Delta V_s))/k_B (T + \Delta T) - 1} - 1} & \text{for } k_z < 0 \\
0 & \text{for } k_z > 0 
\end{cases}
\tag{12}
\]
Here $k_B$ is Boltzmann constant. By substituting Eqs (11) and (12) to Eq (10), for $\Delta T \ll T$ and $|\Delta V_s| \ll |V_s|$, we arrive at

$$\sigma_S S_s = \frac{\pi^2 k_B^2 T}{6\theta^2} \sin^2 \theta$$

(13)

for half metal with ferromagnetic magnons with a quadratic dispersion relation $\omega = Dk^2$, where $D$ is the dispersion constant. By using experimental value $S_s$ [14, 15] we can get $\sigma_s$.

3. Results and Discussion

In the previous Section, we showed that each of the majority and minority spin can generate spin current. Separately, each of the spin acts as conducting and insulating spin. The behaviour of conducting spin agrees with the theoretical and experimental works on spin transport on the metallic ferromagnets [11]. On the other hand, the insulating spin, which is not contributing to the electric current transport, can still contribute to the spin current generation by generating magnonic spin current. This behaviour resemble the behaviour of the magnetic moments of insulating ferromagnets and agrees with the theoretical and experimental works on insulating ferromagnets [14,15,17].

While in each of the metallic and insulating ferromagnets, the spin current are only generated by one of the mechanism, either conducting or insulating electrons. In the case of half-metal, both mechanism can be combined. By writing the accumulative spin and heat current relation, we can find the overall heat and spin current relation

$$
\begin{pmatrix}
\frac{\lambda}{\sigma} \\
\frac{\lambda}{\sigma}
\end{pmatrix} = - \begin{pmatrix}
\sigma (1 - P^2) + \sigma_m & \sigma (P' - P) S + \sigma_m S_m \\
[\sigma (P' - P) S + \sigma_m S_m]T & [\kappa + \kappa_m]T
\end{pmatrix} \begin{pmatrix}
\n(\nu V_s/2) \\
\nu V_s/2
\end{pmatrix},
$$

(14)

where the magnonic contribution to heat conductivity $\kappa_m$ has been studied in Ref. [13]. By looking at the determinant of the $2 \times 2$ matrix, which is the figure of merit $ZT$ of heat current to spin current, one can optimize the parameters to get the most efficient spin current generation. For a particular case of $P = 1$

$$ZT_{P=1} = \frac{\sigma_m S_m^2}{\kappa + \kappa_m} \left( 1 + \frac{\sigma_m (P' - 1)S}{\sigma_m S_m} \right)^2,$$

(15)

such that, the conducting spin can enhance the spin generation of the insulating spin when $P' - 1 > \sigma_m S_m/(\sigma S)$

4. Conclusion

We discuss the mechanism of pure spin current generation in half-metal by looking at the spin transport of each spins. The vanishing density of state of one of the spin may suggest that any spin current is accompanied by electric current. However, the vanishing density of state is not necessarily resulted in vanishing electric conductivity for that particular spin. We show that pure spin current generation, without any electric current, is possible in such a case. Computational modeling can be carried out for estimating the spin-dependent Seebeck effect of half-metals. Furthermore, the full expression of $\sigma_m S_m$, dependency of $\theta$ to $T$ and $k$ need to be considered in order to give a further estimation for real half metallic material. The spin state with vanishing density of state i.e. the insulating spin can also transferred spin current by their collective movement. We demonstrated that magnon can be used to thermally generate spin current in half-metals. Further studies on the relation of magnonic spin current and the spin accumulation are required to write the full magnonic spin-heat matrix relation similar to those of the conduction electron (Eq. (6)). Research on magnonic spin current transfer can lead to the information transfer via magnetic insulator, which can reduce the heat dissipation significantly.
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