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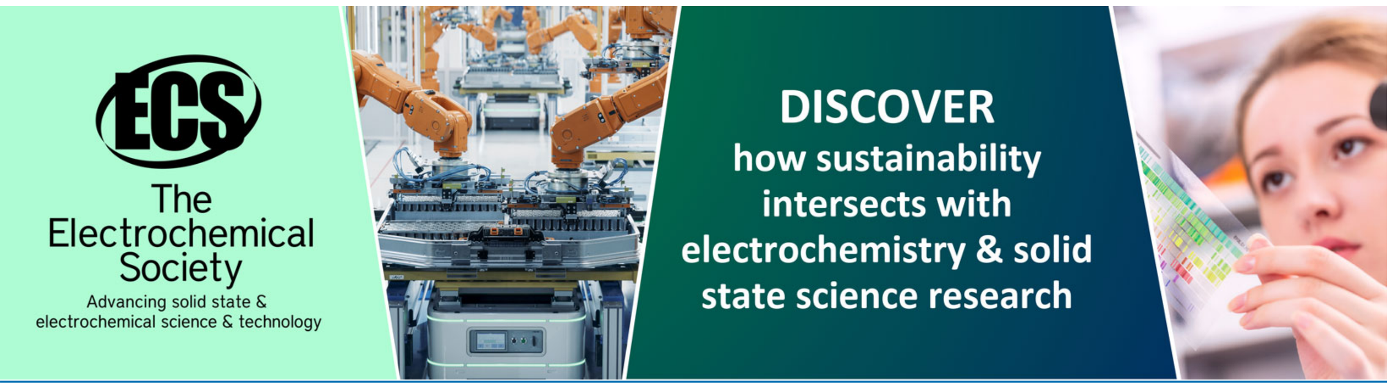

Drop of Spin Polarization of Half Metal due to Interfacial Spin Mixing

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Abstract. Half metal is a ferromagnetic metal that act as a conductor to electrons with of one spin orientation, while act as an insulator for the opposite spin. Because of this high spin-dependent property, half metals are widely studied in spintronics area. This property can be represented by the spin polarization $P = (G_\uparrow - G_\downarrow)/(G_\uparrow + G_\downarrow)$ of its spin-dependent conductances $G_{\uparrow,\downarrow}$. The value of P of an ideal half metal is 1. However, the value of P is reduced when it is attached to other material. We study how the spin current generations that occurs at the interface of half metal and normal metal reduces the value P. At the interface of a half metal and a normal metal a spin current can be pumped from the ferromagnetic layer to the normal metal. This spin pumping effect is characterized by spin-mixing conductance, which represents the magnitude of the generated spin current due to the mixing of electrons with spin up and down. By analyzing the coupling of spin and electric currents in the interface of half metal and normal metal, we show that the spin mixing strongly influences the spin-dependent transport near the interface, and therefore reduces the spin polarization of the half metal.

1. Introduction

Half metal is a ferromagnet with a strong spin-dependent properties[4]. At the Fermi level, the density of state of one of its spin is equal to zero. As a consequent, half-metallic material acts as a conductor only to electrons with one spin orientation. In a two-current model, this property is measured by a spin polarization

$$P = \frac{G_\uparrow - G_\downarrow}{G_\uparrow + G_\downarrow}, \tag{1}$$

where $G_\uparrow$ and $G_\downarrow$ are the conductances of the majority and minority spin, respectively. For an ideal half metal $G_\uparrow \gg G_\downarrow$, therefore $P = 1$.

Spin-dependent band calculations have shown that Heusler alloys and half-Heusler alloys have half-metallic band structures, *i.e.* the density of states of one spin is zero at Fermi level [7, 6]. However, the measured values of spin polarization in experiments has shown values $P < 1$. The measurements of less than 1 values of P may come from the influences of adjacent materials attached to the half metal. Among the phenomena that occurs at the interface of a half metal and an adjacent non-magnetic metal, a recent experiment showed that a pure spin current, a pure angular momentum flow without any electric currents, is transferred through the interface [1]. The quantity that directly related to the spin current generation in Ref. [1] is the spin mixing conductance $g_{\uparrow\downarrow}$. The spin-mixing conductance is the property of the interface where the spin current is generated [13]. While the spin current can also be generated by ferromagnetic resonance [10] or electric voltage [9, 16], the generated spin currents are governed by the same spin-mixing conductances.

Unlike electric current, which is a vector, a spin current is a tensor that can be characterized with a current and a polarization vectors that represents the direction of its movement and its angular momentum direction, respectively [12]. In this article, we use the following definition for spin current tensor

$$\mathbb{J}_s = \frac{1}{2}\left(\mathbf{j}_s \otimes \boldsymbol{\sigma} + \boldsymbol{\sigma} \otimes \mathbf{j}_s\right), \qquad (2)$$

where $\boldsymbol{\sigma}$ is the polarization vector and $\mathbf{j}_s$ is the spin current vector.

In this article, we focuses on the role of the spin-mixing conductance in reducing the measured value of spin polarization P. By utilizing the two-currents model of majority and minority spins [5, 11], we analyze the coupling of the spin and electric currents in the bilayer of a half metal and a non-magnetic metal. The pure spin current generation at the interface reduces the coupling of the spin and electric currents, thus, reduces the measured spin polarization.

2. Spin current distribution

To determine the spin polarization of the conductance in a real system that includes interfaces, we need to consider a ferromagnet (F) sandwiched by non-magnetic metals (N) at $x = \pm l/2$ under an applied voltage V. Here l is the width of the ferromagnet. The non-magnetic metals are assumed to have a large conductance, compared to F, such that the voltage drop in N can be ignored.

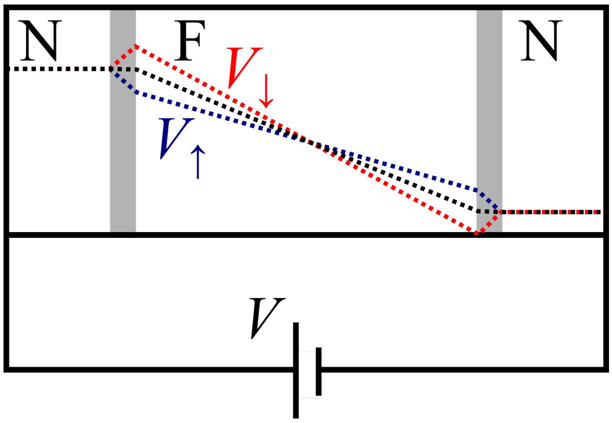

Figure 1. To see the effect of the interface, we consider a ferromagnet (F) sandwiched by non-magnetic metals (N). The large conductances of the non-magnetic metals induces negligible voltage drop at both Ns. In F, the voltage become spin-dependent $V_\uparrow$ and $V_\downarrow$, which corresponds to the majority and minority spins respectively.

2.1. Coupling of spin and charge current in F

We start from a more general ferromagnet with spin-polarization $P_F \leq 1$, the spin-dependent transport can be represented in the following current-force matrix relation

$$\begin{pmatrix} \mathbf{j} \\ \mathbf{j}_s \end{pmatrix} = \sigma_F \begin{pmatrix} 1 & P_F \\ P_F & 1 \end{pmatrix} \begin{pmatrix} -\nabla V \\ -\nabla\left(\boldsymbol{\sigma} \cdot \mathbf{V}_s/2\right) \end{pmatrix}, \qquad (3)$$

where σ_F is the conductivity of F, $V = (V_\uparrow + V_\downarrow)/2$ and $V_s = V_\uparrow - V_\downarrow$ is the electric voltage and spin accumulation, respectively, which are related to the spin dependent voltages. $V_\uparrow$ and $V_\downarrow$ are the voltage of the spin up $\mathbf{j}_\uparrow$ and spin down $\mathbf{j}_\downarrow$ current densities, respectively. Here we limit our discussion of coupling of charge $\mathbf{j} = \mathbf{j}_\uparrow + \mathbf{j}_\downarrow$ and spin $\mathbf{j}_s = \mathbf{j}_\uparrow - \mathbf{j}_\downarrow$ densities in the absence of thermal gradient [2, 8].

Due to spin-flip scattering, the spin current is diffused through F. The diffusion relation can be written in term of a diffusive spin accumulation

$$\nabla^2 \mathbf{V}_s = \frac{\mathbf{V}_s}{\lambda^2}, \tag{4}$$

where λ is the spin-diffusion length. Substituting Eq. 3, the solution is

$$\mathbf{V}_s = \mathbf{V}_0 \frac{\sinh \frac{x}{\lambda}}{\sinh \frac{l}{2\lambda}}. \tag{5}$$

Here we applied the boundary condition of $\mathbf{V}_s(\pm l/2) = \pm \mathbf{V}_0$. Setting $V(0) = 0$, the electric voltage distribution can also be obtained

$$V(x) = -\frac{|\mathbf{j}|\, x}{\sigma} - P_F \boldsymbol{\sigma} \cdot \mathbf{V}_0 \frac{\sinh \frac{x}{\lambda}}{\sinh \frac{l}{2\lambda}} \tag{6}$$

2.2. Spin current generation in F | N interface

At the interface, spin currents also arised due to spin mixing conductance $g^{\uparrow\downarrow} = g_r + i g_i$, namely spin currents associated with spin transfer torques J_{ST} and spin pumping effects J_{SP}. J_{SP} arises from the dynamics of the magnetization vector $\mathbf{m}$ [13]

$$j_{\mathrm{SP}} \boldsymbol{\sigma} \propto g_r \mathbf{m} \times \dot{\mathbf{m}} - g_i \dot{\mathbf{m}}. \tag{7}$$

Proportionality indicates a conversion constant from spin current in Joule unit to Ampere unit. On the other hand, spin transfer torque arises from the relative orientation of directions of magnetization and of spin accumulation [3, 8].

$$j_{\mathrm{ST}} \boldsymbol{\sigma} \propto g_r \mathbf{m} \times (\mathbf{m} \times \Delta \mathbf{V}_s) - g_i \mathbf{m} \times \Delta \mathbf{V}_s, \tag{8}$$

where $\Delta \mathbf{V}_s = \mathbf{V}_s^N - \mathbf{V}_s^F$ is the spin accumulation drop at the interface.

Since generally $\mathrm{Re} g^{\uparrow\downarrow} \gg \mathrm{Im} g^{\uparrow\downarrow}$, we will focus on the g_r term. In steady state, j_{SP} is balanced by backflow of spin current due to (Johnson-Nyquist) thermal fluctuation [15]. Because of that, the interface spin generation effects contribution to the spin current is

$$j_s^{\uparrow\downarrow} \boldsymbol{\sigma} = -g_s \Delta \mathbf{V}_s, \tag{9}$$

where g_s is proportional to g_r [14]

$$g_s = g_r \frac{e \gamma \hbar Z_{3/2}}{\pi M_s d \lambda^3}, \tag{10}$$

γ is the gyromagnetic ratios, M_s saturated magnetization, d is thickness of the ferromagnet, $\lambda \propto T^{-1/2}$ is the de Broglie thermal wavelength of magnon and Z_n is the Zeta function.

When the spin accumulation in the N side is zero (see Fig. 1), the spin current at the interface is then

$$j_s \left(\pm \frac{l}{2} \right) = \mp g_s \boldsymbol{\sigma} \cdot \mathbf{V}_s \left(\pm \frac{l}{2} \right) = g_s \boldsymbol{\sigma} \cdot \mathbf{V}_0. \tag{11}$$

3. Result and Discussion

From the boundary condition for spin current at $\mathbf{j}_s(\pm l/2)$, we can substitute Eq. 6 to Eq. 3 and get the spin and electric current that is measured by the N probes.

$$|\mathbf{j}_s| = |\mathbf{j}| \frac{P_F}{1 + \dfrac{1-P_F^2}{g_s \sigma_F \lambda} \coth \dfrac{l}{2\lambda}}, \tag{12}$$

where

$$|\mathbf{j}| = \frac{V}{\dfrac{l}{\sigma_F} + \dfrac{2P_F}{g_s + \sigma_F \dfrac{1-P^2}{\lambda} \coth \dfrac{l}{2\lambda}}}. \tag{13}$$

The effective spin polarization can be determine by from the spin-dependent conductances

$$G_\uparrow \equiv \frac{|j_\uparrow|\, A}{V_\uparrow} \tag{14}$$

$$G_\downarrow \equiv \frac{|j_\downarrow|\, A}{V_\downarrow}, \tag{15}$$

where A is the cross-sectional area. Since the voltage is no longer spin dependent at the non-magnetic probes (see Fig. 1), the effective polarization is then

$$P = \frac{|j_\uparrow| - |j_\downarrow|}{|j_\uparrow| + |j_\downarrow|} = \frac{|j_s|}{|j|} = \frac{P_F}{1 + \dfrac{g_F}{g_s} \coth \dfrac{l}{2\lambda}}, \tag{16}$$

where $g_F = \sigma_F \lambda/(1-P_F^2)$ is the conductance of F that responds to the spin current. P is determined by g_F/g_s ratio and the length of F. $\coth l/(2\lambda)$ dependency indicates that larger l felt smaller the polarization drop *i.e.* smaller interface effect.

4. Conclusion

We discussed the current transports in multilayer system involving half metals and non-magnetic metals. By taking the limit of very thin non-magnetic metals, we showed that the value of the spin polarization drops because of the interfacial effects represented by G_S, which is proportional to spin mixing conductance.

When spin and electric current do not couple in the interface, the spin polarization will not decrease. We have shown that when the spin current can penetrate the ferromagnetic bulk and therefore couple to electric current, it can reduce the effective spin polarization of the system.

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