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Derivation of dc Voltages in a Magnetic Multilayer Undergoing Ferromagnetic Resonance

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In this work, we present a comprehensive and systematic approach for the derivation of the dc voltage generated by a magnetic multilayer undergoing ferromagnetic resonance, originally derived by Berger. Our alternative derivation applies especially in the limit of the spin diffusion length much longer than the carrier mean free path.

Key words : Voltage, Magnetic multilayer, Ferromagnetic resonance

1. Introduction

In a recent paper, Berger predicted dc voltage generation in so called the SWASER type magnetic multilayer under the ferromagnetic resonance condition [1]. He considered *s*-electron flips in the thin ferromagnetic ("F_2") layer by *d*-spin magnons through the *s-d* exchange interaction, as illustrated in Fig. 1, which shows the inter-spin-band transition by magnon-electron interactions. His formulation, in our opinion, can be valid also in other types of nonmagnetic/multilayers such as asymmetric GMR (giant magnetoresistivity) structures in the CPP (current perpendicular to the plane) configuration [2]. In those systems, the dc voltage can be attributed to the spin flip-induced electrochemical potential at the interface and the spin diffusion processes. Figure 2 shows the chemical potential imbalance between two conduction electron spin systems by magnon excitation at the interface and the resultant spin diffusion. In this work, we show that the results of the Berger's formulation can be derived in a more comprehensive and rigorous way.

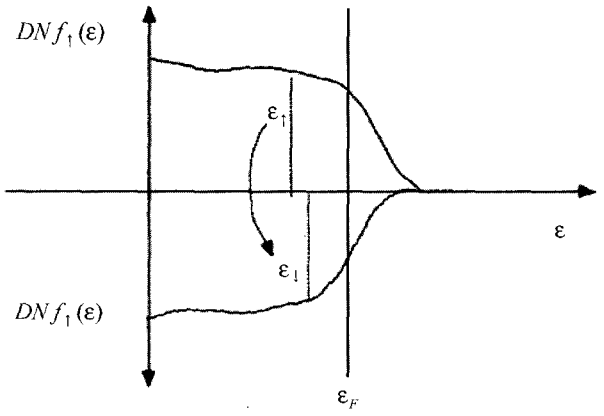

Fig. 1. Inter-spin-band transition by magnon-electron interactions. D_N and $f(\varepsilon)$ are electron density of states and distribution function, respectively.

2. Formulation

In a recent study, Valet and Fert showed that the general

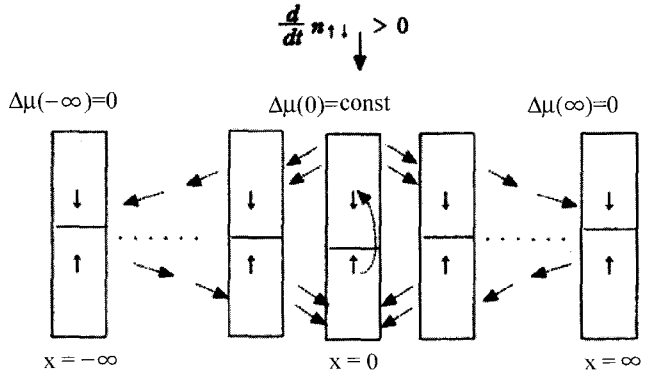

Fig. 2. Chemical potential imbalance between two conduction electron spin systems by magnon excitation at the interface and the resultant spin diffusion.

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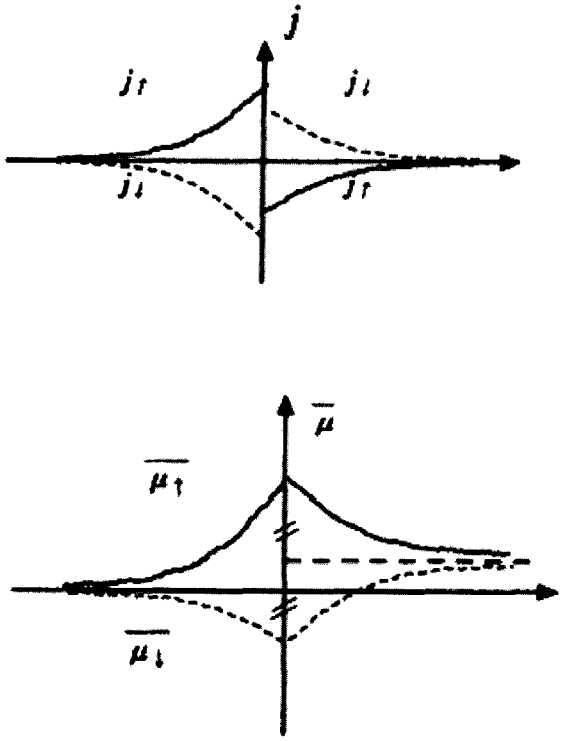

Fig. 3. Spin current and chemical potential for calculation of the magnon-induced dc voltage at the ferro-normal interface.

relation between $j_x^{\uparrow}$, $j_x^{\downarrow}$ (spin-up, spin-down currents) and $\bar{\mu}\uparrow$, $\bar{\mu}\downarrow$ (electrochemical potential of spin-up, spin-down subsystems) can be obtained by reducing the Boltzmann equation to the macroscopic transport equations [3]. They can be presented simply by the spin diffusion and Ohm's law, when the spin diffusion length is much longer than the carrier mean free path. In that case, we can introduce the diffusion equation

$$D\frac{\partial^2}{\partial x^2}\Delta\bar{\mu} = \frac{\partial}{\partial t}\Delta\bar{\mu} \tag{1}$$

for the electrochemical potential difference $\Delta\bar{\mu} = \bar{\mu}_{\uparrow} - \bar{\mu}_{\downarrow}$. Figure 3 shows the spin current and chemical potential for calculation of the magnon-induced dc voltage at the ferro-normal interface. Eq. (1) corresponds to the spin energy diffusion from the interface for non-zero $\Delta\bar{\mu}(x=0)$ by the *s-d* exchange-induced spin flips. Then, in a steady state,

$$D\frac{d^2}{dx^2}\Delta\bar{\mu} = \frac{1}{\tau_{sd}}\Delta\bar{\mu} \quad (\tau_{sd}\text{: spin diffusion time}) \tag{2}$$

or

$$\frac{d^2}{dx^2}(\bar{\mu}\uparrow - \bar{\mu}\downarrow) = \frac{1}{l_{sd}^2}\Delta\bar{\mu}$$
$$(l_{sd} = \sqrt{D\tau_{sd}}\text{: spin diffusion length}) \tag{3}$$

Such a formulation appeared in previous studies for the resistance of ferro/normal metal interfaces by van Son *et al.* and Johnson and Silsbee [4, 5]. One can then obtain the solution $\Delta\mu(x) = \Delta\mu(0)e^{\pm x/l_{sd}}$ from the boundary conditions $\Delta\mu(0) = const.$ and $\Delta\mu(\pm\infty) \rightarrow 0$ [1]. Now, we can substitute

$$j_x^{\uparrow} = \sum_{\uparrow}/e\frac{d\overline{\mu_{\uparrow}}}{dx},\ j_x^{\downarrow} = \sum_{\downarrow}/e\frac{d\overline{\mu_{\downarrow}}}{dx}$$

, Ohm's and Fick's laws in combined form, into Eq. (3) [3, 4].

Assuming an open circuit condition and a steady state charge density with charge conservation,

$$j_x^{\uparrow} + j_x^{\downarrow} = j_x = 0,\ \frac{dj_x^{\uparrow}}{dx} = -\frac{dj_x^{\downarrow}}{dx}\ (\text{for } \frac{dj_x}{dx} = 0). \tag{4}$$

We then have

$$\frac{dj_x^{\uparrow}}{dx} = -\frac{dj_x^{\downarrow}}{dx} = \frac{1}{l_{sd}^2}(e\sum_{\uparrow}{}^{-1} + \sum_{\downarrow}{}^{-1})\Delta\bar{\mu}(x). \tag{5}$$

From $\Delta\mu(x) = \Delta\mu e^{\pm x/l_{sd}}$ and Eq. (5), we now obtain

$$j_x^{\uparrow} = \pm\frac{1}{e\left(\sum_{\uparrow}{}^{-1} + \sum_{\downarrow}{}^{-1}\right)}\frac{\Delta\overline{\mu(0)}}{l_{sd}}e^{\pm x/l_{sd}}$$

$$j_x^{\downarrow} = \pm\frac{1}{e\left(\sum_{\uparrow}{}^{-1} + \sum_{\downarrow}{}^{-1}\right)}\frac{\Delta\overline{\mu(0)}}{l_{sd}}e^{\pm x/l_{sd}} \tag{6a}$$

$$\bar{\mu}_{\uparrow} = c + \frac{1}{\sum_{\uparrow}\left(\sum_{\uparrow}{}^{-1} + \sum_{\downarrow}{}^{-1}\right)}\Delta\bar{\mu}(0)e^{\pm x/l_{sd}}$$

$$\bar{\mu}_{\downarrow} = c - \frac{1}{\sum_{\downarrow}\left(\sum_{\uparrow}{}^{-1} + \sum_{\downarrow}{}^{-1}\right)}\Delta\bar{\mu}(0)e^{\pm x/l_{sd}} \tag{6b}$$

The above results turn out to agree with those in Berger's original work, where a relaxation time was introduced for the one-dimensional conduction. However, adopting the steady state diffusion equation of the electrochemical potential in the beginning, as has been done in this work, appears more natural as it would render the formulation logically coherent and the driving process relatively simpler. Nonetheless, making use of Eqs. (6a) and (6b), which followed from the more natural and rigorous approach of ours, the dc voltage generated by $\Delta\bar{\mu}(0)$ can be shown to be the same as his final expression for the generated DC voltage,

$$V = \left(\frac{\alpha_1 - 1}{\alpha_1 + 1}\right)\left(\frac{\Delta\bar{\mu}}{2e}\right), \tag{7}$$

where $\alpha_1 = \frac{\sum_{\uparrow}}{\sum_{\downarrow}}$ in the thick ferromagnetic ("F_1") region. Here, the continuity of the electrochemical potential at the interface must be supposed, as well as $\sum_{\uparrow} = \sum_{\downarrow}$ in the normal metal region which is the thick nonmagnetic N_2 layer in Berger's aforementioned paper.

In conclusion, we have worked out an alternative derivation of Berger's previous important results for the dc voltage generated by a magnetic multilayer undergoing ferromagnetic resonance. In the process, we have shown that his results can be obtained in a more coherent manner. Our formulations apply for the case of the spin diffusion length much longer than the electron mean free path. Otherwise, there must be an additional perturbation term of the anisotropic part of the electron distribution in the transport equation, which breaks the linear response relation between the electrochemical potential and the current density. However, it may be reasonable to apply the approximation of the sufficiently long spin diffusion length to the systems of interest in the current work.

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