Simple model for detection of spin accumulation in a ferromagnetic double tunnel junction

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Abstract. We study the effect of spin accumulation in ferromagnetic double tunnel junctions based on a simple model. The analytical results for typical cases show that spin accumulation enhances the tunnel magnetoresistance (TMR) effect and furthermore affects electric potential of the center electrode. These effects are possibly used for the detection of spin accumulation in ferromagnetic double tunnel junctions.

1. Introduction
Double-barrier ferromagnetic tunnel junctions are of interest due to their novel spin-dependent transport properties such as efficient current induced magnetization switching [1], spin-dependent resonant tunneling [2,3], spin-dependent single electron tunneling [4-6] and spin accumulation [7-9]. In particular, double tunnel junctions are considered as one of the important systems to investigate physics of spin accumulation since the magnitude of spin splitting of chemical potential due to spin accumulation in double tunnel junctions can be much larger than that in metallic systems.

Detection of spin accumulation in double tunnel junctions was first demonstrated for a GaMnAs/AlAs/GaAs/AlAs/GaMnAs junction [7], in which the center electrode is nonmagnetic so that conventional tunnel magnetoresistance (TMR) described by Julliere’s model [10] does not appear. Only in the case when spin accumulation occurs in the nonmagnetic center electrode, finite TMR is observed as a direct signal of spin accumulation. Theoretical analysis for this phenomenon has also been made by using a simplified model [11]. On the other hand, spin accumulation in a ferromagnetic center electrode cannot be detected in such a simple way. For the purpose, it has been believed that characteristic modification of TMR, such as sign changes, is needed to detect as a signal of spin accumulation. In fact, spin accumulation in a ferromagnetic center electrode consisting of a Co nanoparticle was experimentally and theoretically evidenced by sign changes of TMR [6]. Except for the case of nanoparticles, however, it has not sufficiently been investigated how spin accumulation in a ferromagnetic electrode influences TMR in double tunnel junctions.

In this paper, in order to understand the basic physics of spin accumulation in ferromagnetic double tunnel junctions, we study the effect of spin accumulation in a ferromagnetic center electrode on TMR by using a model simplified as much as Julliere’s model.

2. Models and analytical results
The model we consider is a ferromagnetic double tunnel junction consisting of fixed left and center electrodes and a free right electrode, shown in Fig. 1 (a), in which each ferromagnetic electrode has the same spin polarization of tunneling electrons. In addition, the left and right tunnel barriers have the
same thickness and properties, i.e., the double junction is entirely symmetric in the parallel magnetization alignment, for simplicity. By neglecting the momentum and energy dependence of the tunneling matrix etc., the conductance of spin channel between two ferromagnetic electrodes \((1,2) = (\text{left}, \text{center}) \) or \((\text{center}, \text{right})\) is given as
\[ G_\sigma = \frac{2e^2}{h} |T|^2 D_1 \rho_1 \rho_2, \]
where \(e\) is the electron’s charge, \(\hbar\) is Dirac’s constant, \(|T|^2\) is the constant obtaining from simplification and summation of the tunnel matrix elements, \(D_1\) and \(D_2\) are the densities of states for tunneling electrons with spin \(\sigma\) in the electrodes 1 and 2, respectively.

Based on the current conservation law, currents for parallel (P: \(\uparrow\uparrow\uparrow\)) and antiparallel (AP: \(\uparrow\uparrow\downarrow\)) states, \(I_P\) and \(I_{AP}\), are calculated in the following cases: fast spin relaxation limit and no spin relaxation in the center electrode. Here, it is assumed that no spin mixing occurs during electron tunneling and therefore the tunneling transport is described by the two current model.

2.1. Fast spin relaxation
For P state, \(\uparrow\) and \(\downarrow\) spin states correspond to the majority and minority spin states for all the electrodes, as shown in Fig. 1 (b). Since the electrochemical potential of the center electrode \(eV_c\) is located exactly at the middle point between those of left and right electrodes, the \(\uparrow (\downarrow)\) spin electron current is given as \(j_{\uparrow (\downarrow)} = \frac{2e^2}{h} |T|^2 D_{\uparrow (\downarrow)} \rho_1 \rho_2 (V/2)\) and then the total current \(I_P\) is written as
\[ I_p = j_\uparrow + j_\downarrow = \frac{2e^2}{h} |T|^2 (D_{\uparrow}^2 + D_{\downarrow}^2)(V/2), \] (1)
where \(D_{\uparrow (\downarrow)}\) is the density of states for tunneling electrons with majority (minority) spin and \(V\) is the applied voltage. For AP state, on the other hand, the system becomes asymmetric and the electric potential of the center electrode \(V_c\) is not coincident with \(V/2\). Putting \(\delta = V_c - V/2\), the fact that the total charge current through the left barrier should be the same as that through the right one leads to
\[ I_{AP} = (2\pi e^2/h) |T|^2 (D_{↑}^2 + D_{↓}^2)(V/2 - \delta) = (2\pi e^2/h) |T|^2 (2D_{↑}D_{↓})(V/2 + \delta). \]  

By solving Eq. (2), \( \delta = P^2(V/2) \) and \( V_c = (1+P^2)(V/2) \) where \( P \) is the spin polarization of tunneling electrons defined as \( P = (D_{↑} - D_{↓})/(D_{↑} + D_{↓}) \). Then, TMR ratio is given as

\[ \text{TMR} = (I_P - I_{AP})/I_{AP} = P^2/(1-P^2), \]  

which is half of the well-known Julliere formula [10]. The reason for the reduction of TMR is simply interpreted as the lack of TMR effect at the left barrier. In this case, the double tunnel junction is regarded as a series connection of two junctions.

2.2. No spin relaxation

When no spin relaxation occurs in the center electrode, current conservation through the two barriers should be satisfied for each spin, resulting in the occurrence of spin accumulation for AP state, as shown in Fig. 1 (c). Therefore, \( I_{AP} \) is different from Eq. (2), while the expression of \( I_P \) is the same as Eq. (1) because spin accumulation does not occur for P state. In the center electrode, we write the electrochemical potentials for \( \uparrow \) and \( \downarrow \) spin electrons as \( \mu_{↑} = e(V/2 + \delta_{↑}) \) and \( \mu_{↓} = e(V/2 - \delta_{↓}) \), respectively for AP state (Fig. 2) and obtain the following equations describing the \( \uparrow \) and \( \downarrow \) spin electron current conservation:

\[ j_{↑} = (2\pi e^2/h) |T|^2 D_{↑}^2 (V/2 - \delta_{↑}) = (2\pi e^2/h) |T|^2 D_{↑}D_{↓}(V/2 + \delta_{↑}), \]  

\[ j_{↓} = (2\pi e^2/h) |T|^2 D_{↓}^2 (V/2 + \delta_{↓}) = (2\pi e^2/h) |T|^2 D_{↑}D_{↓}(V/2 - \delta_{↓}). \]  

Eqs. (4) and (5) lead to the magnitude of spin accumulation \( \delta_{↑} = \delta_{↓} = P V/2 \). Using this important equation, Eq. (2) (= \( I_P \)) and the sum of \( j_{↑} \) and \( j_{↓} \) (= \( I_{AP} \)) give TMR ratio different from Eq. (3):

\[ \text{TMR} = (I_P - I_{AP})/I_{AP} = 2P^2/(1-P^2). \]  

This analytical result is in coincidence with the Julliere formula, and it clearly shows that TMR ratio for the change between \((\uparrow \uparrow \uparrow)\) and \((\uparrow \downarrow \downarrow)\) is enhanced by spin accumulation in the center electrode.

The electric potential of the center electrode \( V_c \) (see Fig. 2) is given by the equation for charge neutrality: \( (V/2 + \delta_{↑} - \delta_{↓}) D_{↑}(\text{total}) = (V_c - (V/2 - \delta_{↓})) D_{↓}(\text{total}) \), where \( D_{\text{↑}(\text{total})} \) is the density of states for the conduction electrons with majority(minority) spin at Fermi level and we distinguish \( D_{\text{↑}(\text{total})} \) from \( D_{\text{↓}(\text{total})} \) by the following reason. Although \( G_{o} = (2\pi e^2/h) |T|^2 D_{↑}(\text{total}) \) is a good approximation in a simple model, the densities of states \( D_{\text{↑}}, D_{\text{↓}} \) do not correspond to those obtained from electronic structure calculations because the tunneling matrix elements strongly depend on the wave vector and band indices etc. \( D_{\text{↑}}, D_{\text{↓}} \) can be regarded as densities of states for tunneling electrons, rather than total conduction electrons at Fermi level. In fact, \( P \) derived from TMR effects are “positive” values in Co and NiFe-based tunnel junctions while the spin polarizations of all electrons at Fermi level \( P_0 = (D_{\text{↑}}(\text{total}) - D_{\text{↓}}(\text{total}))/(D_{\text{↑}}(\text{total}) + D_{\text{↓}}(\text{total})) \) given by electronic structure calculations for bulk Co and NiFe are “negative”. The difference in the sign between \( P \) and \( P_0 \) is also taken into account for simulations of spin-dependent single electron tunneling [6].

Using \( \delta_{↑} = \delta_{↓} = P V/2 \), the above equation of charge neutrality can be rewritten with \( P_0 \) as \( V_c = (1+P_0 P)(V/2) \). Note that if \( D_{\text{↑}(\text{total})} = D_{\text{↓}(\text{total})} \), it is identical with the expression for the case of fast spin relaxation. This result suggests that spin accumulation brings about the transition of \( V_c \) (i.e., \( V_c/(V/2) = 1+P^2 \rightarrow 1+P_0 P \)), which may be drastic when the sign of \( P_0 \) is opposite to that of \( P \).

3. Discussion

The simple model calculation shows that spin accumulation enhances the TMR ratio to be twice and also that the electric potential of the center electrode \( V_c \) is affected. For the experimental observation,
however, spin relaxation may much suppress spin accumulation in the center electrode. Here, let us discuss the condition for occurrence of spin accumulation against spin relaxation. Considering that injected spins maintain their spin states on the time scale comparable to the spin relaxation time, we can estimate the electrochemical potential changes $\mu^\uparrow = \mu^\downarrow = eV_c$ and $\mu$ as $\Delta \mu = \Delta \mu^\downarrow = jP\tau_dD_0^\downarrow \frac{P\tau_d}{e}t^{0.75}$, where $\tau_d$ is the spin relaxation time $[6,9]$. Substituting $D_0^\downarrow \tau_d$ into $D^\downarrow$, we obtain $\Delta \mu = jP\tau_d \frac{P\tau_d}{e}t^{0.75}$, where $t$ is the layer thickness of the center electrode, $a$ is the lattice constant and $D_0^\downarrow$ is the density of states per atom for all electrons with spin $\uparrow$ at Fermi level. When we assume that the double junction’s resistance-area product is several $\mu m^2$ and $V \sim 100$ mV, $j$ is evaluated to be a few MA/cm$^2$. Then, assuming that $P \sim 0.5$, $a \sim 0.2 nm$, $\tau_d \sim 1$ psec, $t \sim 1$ nm and $D_0^\downarrow \sim 1$ states/eV/atom, spin accumulation $\Delta \mu \sim 1$ meV is expected to occur in the center electrode. This spin accumulation is small but is not negligible, compared with $V \sim 100$ mV, suggesting that the enhancement of TMR and the modification of $V_c$ due to spin accumulation are possibly detected for low-resistive ferromagnetic double tunnel junctions with a $\sim 1$ nm thick center electrode. If an enhancement of $\tau_d$ occurs as in nanoparticles ($\tau_d > 10$ nsec) $[6,9]$, $\Delta \mu$ is much enhanced and hence these effects of spin accumulation on TMR and $V_c$ should be clearly observed.

4. Summary

We analyze the effects of spin accumulation in symmetric ferromagnetic double tunnel junctions based on a simple model in the fast and no spin relaxation limits. For the change in magnetization configurations between $\left( \uparrow \uparrow \uparrow \right)$ and $\left( \uparrow \uparrow \downarrow \right)$, TMR ratio is enhanced to be twice by spin accumulation in the center electrode. Furthermore, the analytical results suggest that the electric potential of the center electrode could be much affected by spin accumulation. Considering realistic parameters for the properties of ferromagnetic tunnel junctions, it is concluded that spin accumulation is possibly detected through the change in TMR and $V_c$.

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