Spin Polarized Tunneling through a Ferromagnetic Barrier

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We have studied the spin polarized tunneling through a ferromagnetic barrier and concluded that the magnetoresistance ratio will increase significantly. Spin-dependent barrier acts as a spin-filter and gives rise to a strong polarization of the tunneling current. For the asymmetric spin-filter tunneling junction, only a ferromagnetic electrode is required.

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I. Introduction

Several groups have studied the large tunneling magnetoresistance (TMR) in trilayer tunneling junctions [1-2]. These researches follow an earlier work [3] that the tunneling conductance of a Fe/Ge/Co junction has a TMR ratio up to 14% at 4.2 K under zero bias voltage. A simple and widely adopted explanation of TMR is based on the conduction electron spin-polarization of the ferromagnetic layers [3], and the TMR ratio could be expressed as

\[ \frac{AR}{R} = \frac{R_{ap} - R_{p}}{R_{ap}} = 2PP' \]

where \( R_p \) and \( R_{ap} \) stand for the resistance with magnetizations of two ferromagnetic electrodes parallel and antiparallel, respectively. \( P \) and \( P' \) are the conduction electron spin polarization of two ferromagnets, respectively. The TMR ratio is proportional to the product of the spin polarization of both ferromagnets [3, 4]. Although the experimental data of TMR ratio are quite scattered, the trend of the upper limit still seems to follow the rule. Therefore, lots of effort were devoted to search the large polarization ferromagnetic materials. Recently, a trilayer epitaxial tunneling device based on the doped perovskite manganates was reported to have about 50% TMR ratio below 200 K [5]. However, except a few candidates, e.g., \( \text{La}_{0.67}\text{Ca}_{0.33}\text{MnO}_3 \) at low temperature [3], the polarization of transition metal is comparably small and thus TMR ratio is restricted at room temperature. Therefore, before any new, large polarization materials are identified, an alternate way to search the large TMR ratio junction relies on the enhancement of spin polarization from the conventional ferromagnetic materials.
In previous spin-polarized tunneling studies of TMR, polarization of the tunneling current only comes from the different densities of spin-up and spin-down conduction electrons at the Fermi level in the ferromagnetic electrode and the tunneling barrier is spin-independent [4]. For a two-band model [4], the spin polarization decreases very fast with the increasing of the nonmagnetic barrier height and thus the TMR ratio will never become very large. In this paper, instead of a nonmagnetic insulator, we suggest a ferromagnetic insulator as the tunneling barrier. Spin polarization of the tunneling current inside the barrier will be greatly enhanced from the different barrier heights for tunneling electrons with different spin orientations. Observations of a ferromagnetic barrier as a spin-filter have been reported [6-9]. Field emission studies on EuS-coated tungsten tips showed a large polarization of the field-emitted electrons below the Curie temperature of EuS[6]. A tunneling current with the 85% polarization was also detected in Au/EuS/Al tunnel junctions [8]. The large spin polarization results are attributed to the exchange splitting of the spin-up and spin-down electron of the conduction band for the barrier. It has also been suggested that the hysteresis in the tunneling magnetoresistance may be caused by spin-filter phenomena [9].

II. Theory

We will study the spin-filter effect of the tunneling electrons in the junctions. We calculated the TMR of spin-polarized conduction electrons within four regions: a left ferromagnetic electrode, a ferromagnetic insulator, a nonmagnetic metal and another right ferromagnetic electrode (FM_{L}/M/M\text{N}/FM_{x}, Fig. 1). The Schrödinger equation describing the electronic states is

$$H_{\xi}\psi = (E_{\xi} + E_F)\psi,$$

and the single-electron Hamiltonian with a model of the conservation of momentum parallel to the interface is

$$H_{\xi,i} = -\frac{\hbar^2}{2\mu} \left( \frac{d}{d\xi} \right)^2 \xi + E_F + U_{i,\sigma}(\xi) - h_i(\xi)\sigma_1,$$

Subscripts $i(=1,2,3,4)$ represent the ferromagnetic layer FM_{L}, the ferromagnetic barrier(MI), the nonmagnetic metal(M) and the other ferromagnetic layer FM_{x}, respectively. The kinetic energy term is $-\hbar^2/2\mu(d/d\xi)^2\xi$, $\mu$ is the effective mass and $\hbar$ is the Planck constant. For simplicity, we assume the same effective mass for all materials. $U$ is the potential term and $E_F$ is the Fermi level of all metals. The left ferromagnetic electrode and ferromagnetic barrier are strong coupled through the interface and thus the magnetization of barrier is assumed to be pinned by the electrode. For the exchange splitting of the spin-up and spin-down electron, the ferromagnetic barrier is a spin-dependent barrier with a lower barrier for the spin-up electrons and a higher barrier for the spin-down electrons (Fig. 1). The energy splitting of the barrier is $\Delta U = U_1 - U_1$. As in giant magnetoresistance (GMR), a nonmagnetic metal spacer is not only to provide the contrast of parallel and antiparallel of the magnetizations in ferromagnetic electrodes but also to be thin enough to keep the spin memory of the conduction electrons [10]. The internal exchange energy of the $i$-th
FIG. 1. Schematic diagram of the densities of states for an FM/MI/M/FM spin-filter tunneling junction. Curve arrows show electron flow. Tunneling through magnetic barrier from one ferromagnetic electrode into a metal and then the ferromagnetic electrode. The top figure is for the magnetizations in antiparallel state; the bottom figure is for the magnetizations in parallel state.

The ferromagnetic layer is $-\mathbf{h}_i(\vec{\xi})\sigma_i$, where $\mathbf{h}$ is the molecular field and $\sigma$ is the Pauli spin operator. We assume $\mathbf{h}_1$ and $\mathbf{h}_2$ to be along with the corresponding spin quantization axes $\zeta$ and $\zeta'$ with a spanned angle $\phi$.

With an incident plane wave of spin-up electron with unit flux in the FM$_1$ layer, we can determine wave functions in all regions by matching the boundary conditions at the interfaces. The spin and charge transmission coefficients are calculated from the proposed spin Hamiltonian and thus the TMR can be calculated. In our calculations, we assume a spin-dependent rectangular barrier for $0 < \xi < t_1$. The thickness of the metal spacer approaches zero and $h_3 = 0$ inside the metal spacer. After some algebraic manipulations and the proper spinor transformation, the transmission probability ($T_{\sigma\sigma'}$) of the tunneling electrons from the spin-$a$ state in the FM$_1$ layer to the spin-$a'$ state in the FM$_2$ layer can be derived, and they are

$$T_{11'} = 8 \frac{k_1 k_{1'} \alpha^2}{(\kappa_1^2 + k_1^2)(\kappa_1^2 + k_{1'}^2)} e^{-2\kappa_1 t_1} (1 + \cos \phi),$$  \hspace{1cm} (2-a)$$

$$T_{11'} = 8 \frac{k_1 k_{1'} \alpha^2}{(\kappa_1^2 + k_1^2)(\kappa_1^2 + k_{1'}^2)} e^{-2\kappa_1 t_1} (1 - \cos \phi),$$  \hspace{1cm} (2-b)$$

where
\[ k_{i,\sigma} = \sqrt{\frac{2\mu}{\hbar^2}} \sqrt{E_\xi + \text{sgn}(\sigma \xi)} h_i, \quad i = 1, 4, \]

\[ \kappa_{2,\sigma} = \sqrt{\frac{2\mu}{\hbar^2}} \sqrt{U_\sigma - E_\xi}, \quad \sigma = \uparrow, \downarrow. \]

\( \text{sgn}(\sigma \xi) \) is a sign function. From symmetry, we can easily get \( T_{1\downarrow}(\phi) \) and \( T_{1\uparrow}(\phi) \).

The transmission probability of the tunneling electron is

\[ T_{\phi}(\phi) = \left( \kappa_2^2 k_{1\uparrow} + \kappa_1^2 k_{1\downarrow} + \kappa_1^2 k_{\uparrow} + k_{\downarrow}^2 k_{\downarrow} \right) \]

\[
\times \left[ \frac{\kappa_2^2 \kappa_1^2 \kappa_1 e^{-2\kappa_1^2}}{(\kappa_2^2 + k_{\uparrow}^2)(\kappa_2^2 + k_{\downarrow}^2)(\kappa_2^2 + k_{1\downarrow}^2)} \left( 1 + q \cos \phi \right) 
+ \frac{1}{(\kappa_1^2 + k_{\downarrow}^2)(\kappa_1^2 + k_{1\uparrow}^2)(\kappa_1^2 + k_{1\downarrow}^2)} (1 - q \cos \phi) \right],
\]

where the effective spin polarization of the ferromagnet with the FM1/MI/M/FM2 structure, \( q \), is

\[ q = \frac{\kappa_1^2 k_{1\uparrow} + k_{\uparrow}^2 k_{1\downarrow} - \kappa_1^2 k_{1\downarrow} - k_{\downarrow}^2 k_{\downarrow}}{\kappa_1^2 k_{1\uparrow} + k_{\uparrow}^2 k_{1\downarrow} + \kappa_1^2 k_{1\downarrow} + k_{\downarrow}^2 k_{\downarrow}}. \]

Effective spin polarization of a spin-filter junction is a combination of spin polarization of the ferromagnet and the contribution from the interface of the magnetic insulator [4]. For a barrier thickness of 20 – 50 Å, \( \exp(-\kappa_1 l_1) \) is usually much larger than \( \exp(-\kappa_1 l_1) \) for the appropriate ferromagnetic insulator (e.g., for EuS, \( \Delta U=0.36 \text{eV} \) at \( T=4 \text{K} \)) [8]. Therefore, we can neglect the contribution of \( \exp(-\kappa_1 l_1) \) in our calculations for simplicity.

We sum the charge transmission over \( E_\xi \) and \( k_{\xi} \) for occupied states near the Fermi energy \( (E_F) \) at 0 K to obtain the tunneling conductance at the vanishing external voltage [4]. Therefore, for the following calculations of tunneling conductance, \( \kappa \) and \( k_{\xi} \) are only derived from \( E_F \). For a FM1/MI/M/FM2 junction, \( \text{AR}/R \) can be reduced as

\[ \frac{\text{AR}}{R} = \frac{2q}{1 + q}. \]

III. Results and discussions

For \( \kappa_1 \approx \kappa_1, q \) approaches the Slonczewski’s spin polarization, \( P_{FM1/MI}[4] \). For a very large barrier height, \( q \) approaches spin polarization of \( FM2[3] \) (i.e., \( P_{FM2} \)) and for a small barrier height, \( q \) approaches \( -P_{FM2} \) (Fig. 2). For a sufficiently low barrier, the interface reverses the sign of polarization of Fermi surface electrons penetrating from magnets to barrier [4] (Fig. 2). The larger the \( \Delta U \), the less the reversing effect of the spin polarization at the small barrier height. Since the magnetic insulator is pinned by the \( FM1 \).
layer, one of the spin channels in FM<sub>1</sub> is almost completely filtered, and thus both q and TMR ratio only depend on the effective spin polarization of the FM<sub>2</sub> layer. It suggests that only one ferromagnetic electrode is required for our asymmetric spin-filter tunneling junction. Because of the fact that

\[
\left| \frac{2P_{FM_1/MI}}{1 + P_{FM_1/MI}} \right| > \left| \frac{2P_{FM_1/MI}P_{FM_1/MI}}{1 + P_{FM_1/MI}P_{FM_1/MI}} \right|, \quad \text{for} \quad -1 < P_{FM_1/MI} < 1,
\]

the absolute value of TMR ratio for the magnetic barrier must be larger than that for the nonmagnetic barrier. The enhancement of the TMR ratio from the spin-filter effect of the ferromagnetic barrier is quite significant. From our model, a 32% TMR ratio of the Fe/I/Fe junction will shift to a 61% TMR ratio of Fe/MUM/Fe spin-filter junction.

Several particular material parameters [4] are used to demonstrate the spin-filter effect of the ferromagnetic electrodes. For the FM/MI/M/Fe, the FM/MI/M/Co and the FM/MI/M/Ni<sub>j</sub> junctions where FM is the arbitrary ferromagnetic electrode, their TMR ratios are shown in Fig. 3. The bigger the spin polarization of FM<sub>2</sub>, the larger the TMR ratio. TMR ratios of all these spin-filter junctions are much larger than the spin-polarization junctions [4]. Negative TMR ratio at the small barrier height results from the negative effective spin polarization (Fig. 2).

To summarize, we have studied the spin polarized tunneling through a spin-dependent barrier, and we conclude that the spin polarization of the tunneling electron will be amplified for the spin-filter effect. Since the TMR ratio depends on the spin polarization of the conduction electrons, the spin-filter effect should raise the TMR ratio a lot for the enhance-

![FIG. 2. Effective polarization(q) of the tunneling electron versus barrier height (m=K'/K1) for the FM/MI/M/Fe junction. The materials constants are taken from Ref. [4]. The values of K'/K1 for the graphs are 1.00 (solid line), 1.05 (long-dash line), 1.10 (dash-dotted line), and 1.15 (short-dash line), respectively.](image)

![FIG. 3. TMR ratio versus barrier height (m = K'/K1) of FM1/MI/M/FM2 junctions with three different materials of FM2. The materials constants are taken from Ref. [4]. The FM2 of the graphs are Fe (solid line), Co (long-dash line), and Ni (dash-dotted line), respectively. Here we assume exp(-K1t1) > exp(-K1t1), and K1 ≈ K1.](image)
mament of spin polarization. It should be noted that the magnetic insulator breaks the symmetry of the junction and thus $q$ and TMR ratio only depend on spin polarization of the FM$_2$ layer. Our present study can be easily extended to an M/MI/M/FM junction and gets the similar results. In our model, the metal spacer is only a passage for the conduction electron with the memory of their spin. However, it is essential for that it provides a contrast of antiparallel and parallel magnetizations of the ferromagnetic electrodes. We do not take into account of the proximity effect for the metal and ferromagnetic layer. It has been demonstrated that the magnetic potential may be modified by the proximity of the ferromagnetic layer [11] and thus spin accumulation on the interface can affect the conductance of the electrons [12]. We also do not consider the possible spin-dependent scattering at the interface of nonmagnetic metal and ferromagnetic layer [10]; nevertheless, the GMR-type effects should enhance our MR ratio further. Considering the flourishing applications of TMR, the research of the spin-filter tunneling junction is very promising.

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References