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Spin injection in double magnetic tunnel junctions: A tight-binding study

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Abstract

Spin current injection in double magnetic tunnel junctions is investigated theoretically based on conservation of spin and charge currents. Numerical calculations are performed for spin accumulation, current density and spin polarization in Fe/insulator (I) (semiconductor (S))/Co/I(S)/Fe double junctions using generalized formalism based on the non-equilibrium Green's function, which are implemented with recursive calculation of real space Green's function in tight-binding model in linear response region. It is shown that spin accumulation leads to difference in resistance, depending on the direction of applied bias with respect to the magnetization configuration of the double barrier magnetic tunnel junctions.

Keywords: Spin injection; Magnetic tunnel junction; Spin accumulation; Tunneling magnetoresistance

1. Introduction

Motivated by potential technological applications as well as the fascinating physics behind spin dependent phenomena in spintronics [1–3], extensive efforts have been made in the investigation of spin current injection from both practical and theoretical points of view [4–9], which promises the possibility of a new class in magnetic memories without the use of magnetic field, and provides a new means to excite and probe the dynamics of nanoscale magnetic states.

Effective and efficient electrical injection of strongly spin-polarized current is a prerequisite for potential successful application of a wide range of possible spin dependent phenomena in the rapidly emerging field. It was reported that tunnel contacts could actually increase the spin injection efficiency from ferromagnet (FM) into two-dimensional electron gas [10] or semiconductor due to its ability to support a considerable difference in electrochemical potentials assuming slow spin relaxation [11], and spin dependent resonant tunneling enhances tunneling magnetoresistance dramatically in double barrier magnetic junctions [12]. While a new field is emerging, where one wants to inject spin current, transfer and manipulate

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the spin information to realize potential spintronics devices, our theoretical understanding is still evolving.

Spin accumulation generated by the injection of spin current is involved in various spin dependent effects and plays an important role. In this paper, a theoretical study is presented on the bias dependence of spin-polarized transport in quantum region in double magnetic tunnel junctions (DMTJ) based on conservation of spin and charge currents. Analytical expression for spin accumulation is derived as a function of bias voltage and transmission probabilities. Spin accumulation, current density and spin polarization are evaluated for Fe/I(S)/Co/I(S)/Fe DMTJ based on the non-equilibrium Green's function formalism, which was generalized for spin systems in linear response region at zero temperature limit [13]. Magnetic configurations will be considered where FM is single domain in our treatment.

2. Theoretical treatment

Consider a double junction structure as illustrated in Fig. 1(a) with magnetizations in the left and right ferromagnetic (FM) electrodes anti-parallel to each other, since there is no spin accumulation when magnetic moments in FM1 (**M1**) and FM3 (**M3**) are parallel for symmetric structures. The relative angle between **M1** (**M3**) and M2 of the left (right) and the middle FMs is $\theta(\pi-\theta)$. Bias voltage applied across FM1 and FM3 causes a spin polarized tunneling injection due to the exchange splitting of FM electrode, and spin accumulation occurs in middle FM layer since a difference in electrochemical potentials for up- and down-spin channels (as shown in Fig. 1(b)) occurs.

The coupling between conduction electron spins and the magnetic moment is taken into account by local s-d type exchange interaction, the second quantization expression for tight-binding Hamiltonian with a nearest-neighbor hopping reads [13,14]

$$H=\sum_{\mathbf{r},\alpha,\beta}\left(\varepsilon_{\mathbf{r}}\delta_{\alpha\beta}+\frac{\gamma_{\mathbf{r}}}{2}\vec{\mu}_{\mathbf{r}}\cdot\vec{\sigma}_{\alpha\beta}\right)c^{+}_{\mathbf{r},\alpha}c_{\mathbf{r},\beta}+t\sum_{\langle\mathbf{r},\mathbf{r}'\rangle\alpha}c^{+}_{\mathbf{r},\alpha}c_{\mathbf{r}',\alpha}+\sum_{\mathbf{r},\alpha}\Phi_{\mathbf{r}}c^{+}_{\mathbf{r},\alpha}c_{\mathbf{r},\alpha} \tag{1a}$$

$$t=-\frac{\hbar^2}{2m^{*}a^2}, \tag{1b}$$

where $\mathbf{r}$ and $\alpha(\beta)$ are spatial and spin indices, respectively, $\gamma_{\mathbf{r}}$ the exchange splitting at magnetic site, $\delta_{\alpha\beta}$ the delta function, $\vec{\mu}_{\mathbf{r}}$ the unit vector of the magnetization, m^{*} and ħ the effective mass of electron and Plank constant, respectively. $c^{+}_{\mathbf{r},\alpha}(c_{\mathbf{r},\alpha})$ the creation (annihilation) operator with spin α at site $\mathbf{r}$, $\varepsilon_{\mathbf{r}}$ the on-site energy, a lattice constant, $\vec{\sigma}_{\alpha\beta}$ the Pauli operator with the matrix elements $\sigma^{x}_{\alpha\beta}$, $\sigma^{y}_{\alpha\beta}$, and $\sigma^{z}_{\alpha\beta}$. Φ_r the electrostatic potential with Φ_r = eV/2 in the left and Φ_r = – eV/2 in the right electrodes, assuming a linear potential drops across the sample when small bias voltage V is applied between the left and right FMs. The summation <**r**, **r**'> runs over nearest-neighbor sites. All energies are measured in unit of nearest-neighbor hopping integral $|t|$, which is the same for all pairs

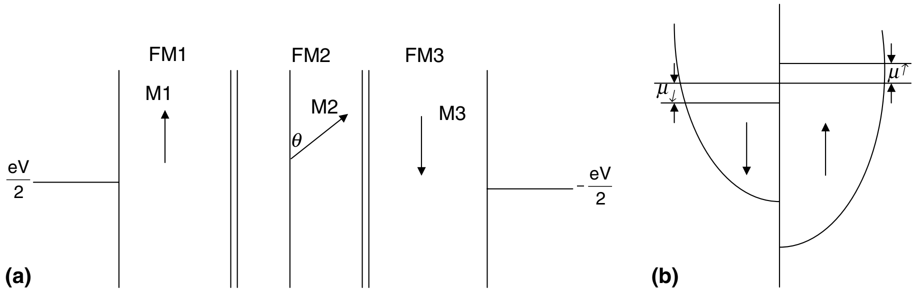

Fig. 1. (a) Schematic illustration of FM1 (M1)/I(S)/FM2 (M2)/I(S)/FM3 (M3) double junction structures with four monolayers (ML) of insulator (semiconductor) and 6 ML of FM2. θ is the angle between the magnetic moments in the left (**M**1) and the middle (**M**2) FMs, V is the applied bias voltage. (b) spin-dependent electrochemical potential $\mu_{\uparrow(\downarrow)}$ for up (down) spin.