Large and controllable tunneling magnetoresistance in ferromagnetic/magnetic-semiconductor/ferromagnetic trilayers

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In this work, we selected a magnetic-semiconductor as an interlayer and investigated the electronic transport properties in the ferromagnetic/ferromagnetic-semiconductor/ferromagnetic (FM/FS/FM) trilayers. The results indicate that the large TMR comparable to that in ferromagnetic/metal oxide/ferromagnetic sandwich can be obtained in the FM/FS/FM multilayers considering the spin filter effect in the magnetic semiconductor layer. Moreover, the transmission coefficient and TMR can be tuned through thickness, Rashba spin-orbit coupling strength and molecular field of the magnetic semiconductor. Our calculations could provide a way to design the semiconductor spintronic devices with excellent and controllable properties.

magnetic semiconductor, spin-orbit coupling, transmission coefficient, tunneling magnetoresistance

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1 Introduction

Semiconductor spintronics [1–3], incorporating additional magnetic features into semiconductor materials, has been a focus of research interest in the past decade. As is evidenced, the efficient spin transport and spin manipulation have been achieved in semiconductors [4] and magnetic multilayers made of semiconductors can be monolithically integrated into semiconductor circuitry. As such, it is believed that semiconductors have good potential in the next-generation spintronic devices. In particular, ferromagnetic/semiconductor/ferromagnetic (F/S/F) multilayered structure, in which spin can be injected into non-magnetic semiconductor, has recently stimulated intensive research interest [5–7], both experimentally and theoretically. Conversely, in the ferromagnetic/nonmagnetic insulator (semiconductor)/ferromagnetic sandwich structure, the magnetic tunneling junction (MTJ) with a considerable variation of the electrical resistance by controlling the magnetization in ferromagnetic electrodes, has also been widely investigated since multilayers with semiconducting nonmagnetic layers are expected to have an advantage over the all-metal system owing to the possible control of the carrier concentration by external parameters [8]. For example, magnetoresistance (MR) of 0.01%–0.5% has been observed in Fe/Si multilayers [9] and MnGa/GaAs/MnGa trilayers [10]. Although the calculation of Li et al. [11] indicated that the larger MR could be obtained in F/S/F nanostructures by considering the Rashba spin-orbit interaction, more research effort is needed to develop the semiconductor spintronics with TMR comparable to that of ferromagnetic/metal oxide/ferromagnetic sandwich structure (large TMR up to 200%) [12].

Spin filtering is suggested to be a nearly ideal method for spin injection into semiconductors and also enable alternate spintronic devices since the principle of spin filtering with magnetic semiconductors has been demonstrated in field...
emission experimentation [13]. Thereafter, the spin-polarized electronic transport properties of magnetic tunneling junctions with magnetic semiconductors are critical. Recently, Fiedler et al. [14] promoted the efficiency of spin injection by inserting a magnetic semiconductor at the interface of ferromagnetic metal and semiconductor. Tanaka et al. [15] observed the phenomenon of magnetoresistance effect in (GaMn)As/AlAs/(GaMn)As tunneling junction, which has generated other investigations. Satoshi et al. [16] laid special stress on analyzing the influence of the drain bias $V_{DS}$ on the spin-polarized current in FM/FS/FM field effect transistor structure. Gajek et al. [17] observed a large TMR in tunnel junction with a multiferroic barrier (La0.1Bi0.9MnO3). In this work, we choose magnetic semiconductor as barrier instead of the insulating and ferromagnetic oxide to investigate the spin-transport properties in a MTJ structure because magnetic semiconductors have the spin-filter effect and their spin relaxation time can be well controlled by doping [18]; and the electrical manipulation of magnetization reversal is available in a ferromagnetic semiconductor [19].

2 Methodology

By using the suggested Slonczewski’s free-electron approximation [20], as well as the transfer matrix method and quantum coherent transport theory of Mireles and Kirczewo [21,22], the effects of Rashba spin-orbit coupling and length of magnetic semiconductor on transmission coefficient and TMR are simultaneously investigated. Furthermore, the dependence of tunneling conductance on Rashba spin-orbit coupling is also discussed. The numerical results indicate that the spin valve effect can be modified by spin filter effect in the magnetic semiconductor. A giant TMR can be obtained by selecting some moderate parameters. Our studies suggest that ferromagnetic semiconductors have good prospects for spintronics applications, which actualize commendably intrinsic properties of spin and charge.

In the system shown as Figure 1, electrons can traverse through the trilayers structure from the left electrode ($x<0$) to the right electrode ($x>d$). Applied external voltage in the $y$ direction gives rise to the Rashba spin-orbit interaction in the magnetic semiconductor. The magnetic moments of the two ferromagnetic electrodes are pinned to the parallel state. The magnetic semiconductor has a role in the spin filter, which obtains an electron of spin parallel to the magnetization of the magnetic semiconductor region across with ease, and vice versa. We now consider the one-dimensional symmetrized version of the Rashba Hamiltonian, the electronic Hamiltonians in FM regions of $x<0$ and $x>d$ and FS regions of $0<x<d$ can be described as

\[ H_{x} = \frac{1}{2} \hat{p}_{x} \frac{1}{m_{f}} \hat{p}_{x} + h_{1}(x) \cdot \sigma, \]  

(1)

and

\[ H_{b} = \frac{1}{2} \hat{p}_{x} \frac{1}{m_{fs}} \hat{p}_{x} + \frac{1}{2} \sigma \left[ \hat{p}_{x} \alpha_{R} + \alpha_{L} \hat{p}_{x} \right] + \delta E + h_{2}(x) \cdot \sigma, \]  

(2)

Here, $m_f^*$ and $m_{fs}^*$ are the effective mass in FM and FS, $\delta E$ is the conduction band mismatch between the ferromagnetic electrodes and the magnetic semiconductor, $\sigma$ denotes the spin Pauli matrices, $\alpha_R$ is the spin-orbit Rashba parameter, $h_1$ and $h_2$ are the exchange splitting energy for ferromagnetic electrodes and magnetic semiconductors, respectively.

Based on one-dimensional symmetrized version of the Rashba Hamiltonian, we can write the eigstates of the FM/FS/FM trilayers structure. The eigenfunction in ferromagnetic regions are $\psi_{r}^{''} = A_1 e^{i\beta_1} + B_1 e^{-i\beta_1}$, and the Fermi wave vector in the ferromagnetic regions is $k_{r}^{'} = \sqrt{2m_{r}^{'}(E-h_{1})/\hbar^2}$. Here $\beta = \pm 1$, denote spin-up $\uparrow$ and spin-down $\downarrow$, $r =$L, R indicates the left and the right ferromagnetic electrodes, $E$ is the energy of a tunneling electron.

In the magnetic semiconductor region, eigenfunctions become $\psi_{l}^{''} = C_{11} e^{i\beta_{11}} + D_{11} e^{-i\beta_{11}}$, and the corresponding Fermi wave vectors $k_1$, $k_2$, $k_3$, and $k_4$ are $\sqrt{2m_{r}^{'}(E-h_{2})/\hbar^2} + k_{r}^{'}$, $\sqrt{2m_{r}^{'}(E-h_{2})/\hbar^2} - k_{r}^{'}$, $\sqrt{2m_{r}^{'}(E+h_{2})/\hbar^2} + k_{r}^{'}$, $\sqrt{2m_{r}^{'}(E+h_{2})/\hbar^2} - k_{r}^{'}$, respectively. Here $k_{r}^{'} = m_{f}^{'} \alpha_{R}/\hbar^2$ is Rashba spin-orbit wave vector, and the absolute value between the vectors of the incoming wave and the reflected one is $2k_{r}^{'}$. The matching conditions for wave functions at $x=0$ and

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**Figure 1** Schematic diagram of FM/FS/FM trilayers structure, $d$ is the length of the magnetic semiconductor.