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Effects of spin-orbit interaction and magnetic field on the electron transport in quasi-1D ferromagnetic/semiconductor/ferromagnetic system*

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Based on the transfer matrix method, we investigate the effects of Rashba spin-orbit interaction and magnetic field on the electron transport in a quasi one-dimensional FM/S/FM system, where FM and S represent the ferromagnetic metal and semiconductor, respectively. The results show that the oscillating scope of the transmission increases with the magnetic field increasing. In the antiferromagnetic alignment, the spin-up and spin-down electrons make the same contribution to the transmission even if a magnetic field is applied. In the ferromagnetic alignment, however, at certain strengths of Rashba spin-orbit interaction and of magnetic field, the transmission coefficient for spin-up electrons is larger than that for spin-down electrons, and the sign of the spin polarization changes, which is opposite to that in the absence of the magnetic field.

Keywords: Rashba spin-orbit interaction, magnetic field, transmission, spin filter effect
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1. Introduction

Rashba spin-orbit coupling in a ferromagnetic (FM) / semiconductor (S) spin transistor has been extensively studied theoretically and experimentally.[1−9] The spin-polarized field effect in a spin transistor originates from the spin precession controlled by an external electric field via spin-orbit coupling (Rashba coupling). The modulation of the Rashba coupling has been demonstrated in a variety of semiconductor materials.[10−12] Besides the gate voltage control of the Rashba coupling, high spin injection efficiency is another important factor for a spin transistor to be efficiently workable. In order to obtain high spin injection, resistive spin-selective contacts[13] and appropriate epitaxial interfaces[14] have been proposed. In experiments, different types of tunnel contacts, such as scanning tunnelling microscopy (STM) tips[15] and resonant double barriers,[16] have been successfully used. Very recently, relatively high spin-injection efficiencies have been achieved in Fe/GaAs-based light emitting diode structures.[17] Such a high spin-polarized electric current is of benefit to our deep study of the spin-polarized transport properties in various heterostructures.

Spin-dependent transport in FM/S/FM sandwiched heterojunctions has been widely investigated, and many basic mechanisms have been established.[18−20] In this type of sandwiched structure, quantum effects have a considerable influence on spin signals. Mireles and Kirczenow[19] presented a theory on the coherent quantum transport in an FM/S/FM system within the Landauer framework of ballistic transport. Cahay and Bandyopadhyay[20] calculated the spin transistor's conductance as a function of the gate voltage and showed that Ramsauer oscillations could be the dominant source of conductance modulation in an 1D-gate-controlled electron spin transistor. Besides the gate voltage control of the Rashba coupling, the effect of magnetic field on the transmission in semiconductor is very important. Up to now, however, we have not found any report about the effects of Rashba spin-orbit interaction and

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magnetic field on a quasi-one-dimensional FM/S/FM system.

Based on the transfer matrix method, we investigate in this article the effects of Rashba spin-orbit interaction and magnetic field on the electron transport properties in a quasi-one-dimensional FM/S/FM system. The results show that the transmission coefficient oscillates more rapidly when the strength of the spin-orbit interaction becomes large, and the phase of the transmission coefficient shifts when the magnetic field increases.

This paper is organized as follows. In Section 2, we describe briefly the Hamiltonian, the relation between the wavenumber and the energy, and the formula of the transmission coefficient in an FM/S/FM system. Numerical results and discussion are shown in Section 3. Section 4 is devoted to a brief summary.

2. Method

Let us consider a quasi-one-dimensional FM / S / FM system shown in Fig.1. That the electrons transport along x axis and then are confined in the y direction in S gives rise to the spin-orbit interaction. If $w \ll \hbar^2/\alpha_{\rm R} m^*$, the intersubband mixing can be neglected. Therefore, under a magnetic field applied, the Hamiltonian reads[19,21]

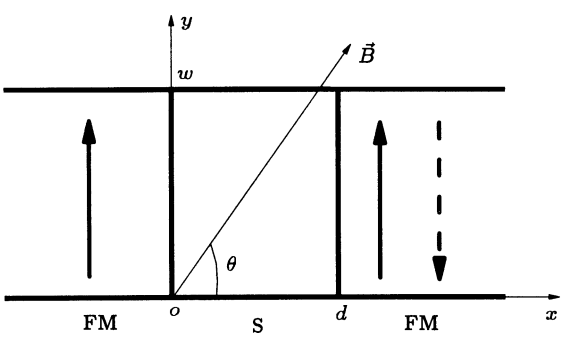


Fig.1. The schematic diagram of a quasi-one-dimensional FM / S / FM system.

$$\widehat{H}_{\rm f} = \frac{1}{2}\widehat{p}_x \frac{1}{m_{\rm f}^*}\widehat{p}_x + \frac{1}{2}\sigma_z \vec{h} \tag{1}$$

in FM and

$$\widehat{H}_{\rm s} = \frac{1}{2}\widehat{p}_x \frac{1}{m_{\rm s}^*}\widehat{p}_x + \frac{1}{2\hbar}\sigma_z[\widehat{p}_x \alpha_{\rm R}(x) + \alpha_{\rm R}(x)\widehat{p}_x] + \frac{g^*\mu_{\rm B}}{2}\sigma_z B + \delta E \tag{2}$$

in S. Here, $m_{\rm f}^*$ and $m_{\rm s}^*$ are respectively the effective mass in FM and S, $\vec{h}$ is the exchange splitting energy in FM, σ_z denotes the spin Pauli matrix, $\alpha_{\rm R}$ is the spin-orbit Rashba parameter, and δE is the conduction band mismatch between FM and S. g^* is the effective g factor, and $\mu_{\rm B}$ is the Bohr magneton. We assume that the total magnetic field experienced by electrons is in the $x-y$ plane, i.e. $\vec{B} = B_x\widehat{x} + B_y\widehat{y}$. In our approximation, the magnetic field does not enter into Eq.(2) through the vector potential. The relations between the wavenumber and the energy are

$$E_{\rm f}^{\sigma}(k_{\rm f}) = \frac{\hbar^2}{2m_{\rm f}^*}(k_{\rm f})^2 + \frac{1}{2}\lambda_\sigma h, \tag{3}$$

$$E_{\rm s}^{\sigma} = \frac{\hbar^2}{2m_{\rm s}^*}(k_{\rm s})^2 + \lambda_\sigma\left[\left(\frac{g^*\mu_{\rm B}B}{2}\right)^2 + g^*\mu_{\rm B}\alpha_{\rm R}k_{\rm s}B\sin\theta + (\alpha_{\rm R}k_{\rm s})^2\right]^{1/2}. \tag{4}$$

Since the Hamiltonian (1) and the Hamiltonian (2) are all spin diagonal, the wavefunctions in FM can be written as

$$\psi_\sigma^v = A_\sigma^v {\rm e}^{{\rm i}k_\sigma^v x} + B_\sigma^v {\rm e}^{-{\rm i}k_\sigma^v x}, \tag{5}$$

where $\sigma(=\uparrow$ or $\downarrow)$ indicates the spin state of the split band, $v = L(R)$ denotes the left (right) FM, and k_σ^v is the Fermi wavevector of σ state in v FM. In the S region, the wavefunctions become

$$\psi_\uparrow^{\rm s} = C_\uparrow {\rm e}^{{\rm i}k_\uparrow^{\rm s} x} + D_\uparrow {\rm e}^{-{\rm i}k_\downarrow^{\rm s} x} \tag{6}$$

and

$$\psi_\downarrow^{\rm s} = C_\downarrow {\rm e}^{{\rm i}k_\downarrow^{\rm s} x} + D_\downarrow {\rm e}^{-{\rm i}k_\uparrow^{\rm s} x}. \tag{7}$$

At the interface, the wavefunction and the probability currents must be continuous,[19,21] thus the transmission coefficient for the ferromagnetic alignment (P) is

$$T_\sigma^{\rm P} = \frac{4\mu^2 k_\sigma^{\rm L} k_\sigma^{\rm R}(k_\uparrow^{\rm s} + k_\downarrow^{\rm s})^2}{k_{\sigma+}^2 + k_{\sigma-}^2 - 2k_{\sigma+}k_{\sigma-}\cos[(k_\uparrow^{\rm s} + k_\downarrow^{\rm s})l_{\rm S}]}, \tag{8}$$

where $k_{\sigma\pm} = (K_{\rm S} \pm \mu k_\sigma^{\rm L})(K_{\rm S} \pm \mu k_\sigma^{\rm R})$ with $K_{\rm S} = k_\sigma^{\rm s} + \lambda_\sigma k_{\rm R}$. $K_{\rm S}$ can be solved by use of energy conservation. For the antiferromagnetic alignment (AP), the transmission coefficient $T_\sigma^{\rm AP}$ is given by Eq. (8) with the replacement $k_\sigma^{\rm R} \to k_{-\sigma}^{\rm L}$.

To study the spin polarization effect, it is useful to calculate the spin polarization of the transport defined as

$$P = \frac{T_\uparrow - T_\downarrow}{T_\uparrow + T_\downarrow}. \tag{9}$$

3. Result and discussion

In calculation, we assume[21] $m_{\rm s}^* = 0.036 m_{\rm e}$ in S and $m_{\rm f}^* = m_{\rm e}$ in FM, where $m_{\rm e}$ is the free-electron

mass, $|\vec{h}| = 3.46\text{eV}$, $E_\text{f} = 2.47\text{eV}$, $\delta E = 2.4\text{eV}$, the unit of the strength of the Rashba spin-orbit interaction $k_0 = 1.0 \times 10^5 \text{cm}^{-1}$; and $\theta = \pi/2$. The values of Zeeman energy $\gamma = \frac{1}{2} g^* \mu_\text{B} B$ used in the calculation will be given below.

The transmission calculations as a function of the length of semiconductor under different magnetic fields are shown in Fig.2. Because the spin-orbit coupling in a semiconductor nanowire can be seen as an effective spin-dependent vector potential, the wavefunction gathers an Aheronov–Bohm phase, which changes sign as the spin is injected into the wire. From Fig.2, it can be seen that the transmission coefficient oscillates with the variation of the length of semiconductor. When the magnetic field increases, the resonant peaks shift toward the left, implying the transmission phase is changed. For example, when no magnetic field is applied, the position of the first valley for the ferromagnetic alignment (the solid and dotted lines in Fig.2(a)) is at about 0.958μm. If the magnetic field is increased to $0.004E_\text{F}$, at the same position, the first resonant peak of the transmission appears, indicating that the phase has shifted $\pi/2$. On the other hand, due to electron cyclotron resonance, the swing of the oscillation becomes larger. Because the magnetic field does not change the barrier structure of the system, the spin-up and spin-down electrons make the same contribution to the transmission in the antiferromagnetic alignment (the dashed lines in Figs.2(a)–(c)).

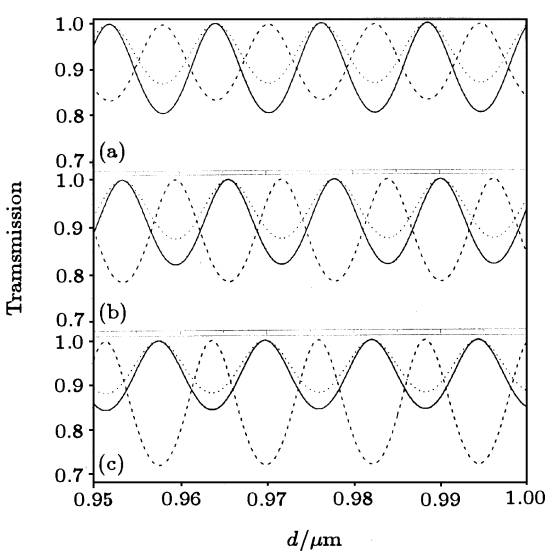


Fig.2. Transmission coefficients against the length d of the semiconductor for $k_\text{R} = 1.0k_0$ under different magnetic fields: (a) $\gamma = 0$, (b) $\gamma = 0.002E_\text{F}$, (c) $\gamma = 0.004E_\text{F}$. The solid, dotted, and dashed lines correspond to $T^\text{P}_\uparrow$, $T^\text{P}_\downarrow$, and $T^\text{AP}_\uparrow$ $(=T^\text{AP}_\downarrow)$, respectively.

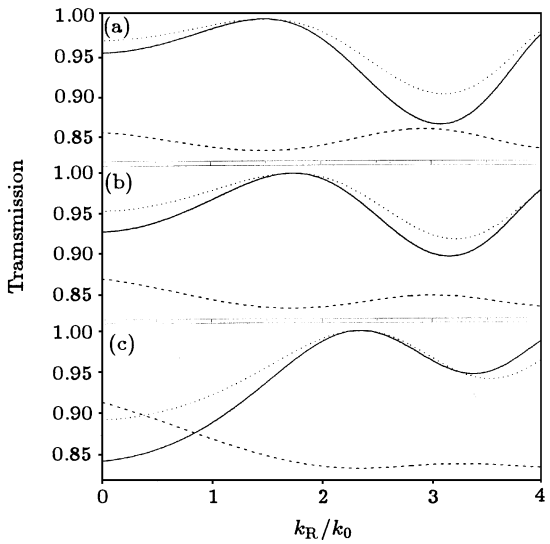


Fig.3. Transmission coefficients as a function of Rashba parameter with a fixed length of the semiconductor ($d = 1.0\mu$m) under different magnetic fields: (a) $\gamma = 0$, (b) $\gamma = 0.002E_\text{F}$, (c) $\gamma = 0.004E_\text{F}$. The solid, dotted, and dashed lines correspond to $T^\text{P}_\uparrow$, $T^\text{P}_\downarrow$, and $T^\text{AP}_\uparrow$ $(=T^\text{AP}_\downarrow)$, respectively.

In Fig.3, the calculated transmission coefficient is plotted as a function of the spin-orbit strength under different magnetic fields with a length of semiconductor fixed ($d = 1.0\mu$m). The curves in the three cases are all in oscillating form and oscillate rapidly as k_R/k_0 increases.

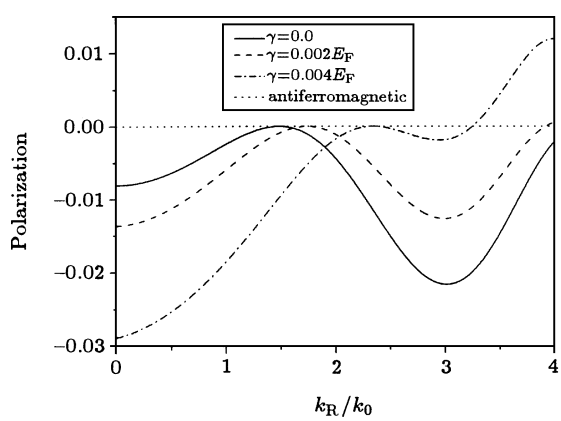


Fig.4. Spin-polarization as a function of Rashba parameter under different magnetic fields with $d = 1.0\mu$m fixed.

In order to reveal the contribution of different spin electrons to the transmission, as well as to study the spin filter effect, we calculate the spin-polarization as a function of Rashba parameter under different magnetic fields. The results are presented in Fig.4. The dotted line in there denotes the spin-polarization in the antiferromagnetic alignment. Because the spin-up

and spin-down electrons in the antiferromagnetic configuration experience the same barrier structure, the spin polarization is zero even when a magnetic field is applied. In the case of ferromagnetic alignment, we find the spin polarization to be modified by the magnetic field. An important phenomenon is that the spin polarization can change its sign at a certain Rashba parameter under a magnetic field of $0.004E_{\mathrm{F}}$ (dash-dotted line in Fig.4). It means that by adjusting the magnetic field, the spin flip and a highly polarized spin current can be achieved under a certain spin-orbit interaction.

4. Summary

Based on the transfer matrix method, the spin-dependent transport and the spin filter effect of electron in a quasi-one-dimensional FM/S/FM system are studied with the effects of Rashba spin-orbit interaction and magnetic field taken into account. The phase of the transmission can be shifted by magnetic fields. In an antiferromagnetic alignment, spin-up and spin-down electrons make the same contribution to transmission even with a magnetic field applied. At certain strengths of Rashba spin-orbit interaction and magnetic field, the transmission coefficient for spin-up electrons in a ferromagnetic alignment is larger than that for spin-down electrons, implying that the spin polarization changes its sign, which is opposite to that in the absence of the magnetic field.

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