Co-ordination between Rashba spin-orbital interaction and space charge effect and enhanced spin injection into semiconductors

Wei Wu1, Jinbin Li1, Yue Yu1 and S. T. Chui2
1. Institute of Theoretical Physics, Chinese Academy of Sciences, P.O. Box 2735, Beijing 100080, China
2. Bartol Research Institute, University of Delaware, Newark, DE 19716
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We consider the effect of the Rashba spin-orbital interaction and space charge in a ferromagnet-insulator/semiconductor/insulator-ferromagnet junction where the spin current is severely affected by the doping, band structure and charge screening in the semiconductor. In diffusion region, if the reduction of the tunneling barriers is comparable to the semiconductor resistance, the magnetoresistance of this junction can be greatly enhanced under appropriate doping by the co-ordination between the Rashba effect and screened Coulomb interaction in the nonequilibrium transport processes within Hartree approximation.

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The spintronics is interesting since this involves exploration of the extra degrees of freedom provided by electron spin, in addition to those due to electron charge, which is believed to be very useful in manipulating future electronic devices [1]. To realize such a spin device, the Rashba spin-orbit interaction is often considered [2]. Since this is caused by structural inversion asymmetry in quantum wells, it can be artificially controlled by adjusting the applied gate voltages and specifically designing the heterostructure [3].

On the other hand, one of the current focus in spintronics lies in injecting spin polarized electrons into non-magnetic semiconductors [4–9]. This is partially motivated by the high magnetoresistance observed in ferromagnet tunnel junctions [10]. However, in the diffusion region and the room temperature, experiments have so far observed a small magnetoresistance ratio of 1% [11,12] in ferromagnet/semiconductor/ferromagnet structures.

Rashba proposed a ferromagnetic metal/tunneling-insulator/semiconductor (FIS) junction to improve the spin injection rate [15]. Many different geometries of the tunneling junction were discussed in Ref. [16]. It is possible that to lift the magnetoresistance to near 10% with a very high electric field [17].

In a recent work [18], we investigated the space charge effect in the nonequilibrium transport process within the Hartree approximation and found that the magnetoresistance of a double FIS junction could be greatly increased if one carefully adjusts the parameters of the junction, such as the charge screening length and the size of the semiconductor. The space charge effect in the nonequilibrium transport process first was found playing an important role in the characteristics of the device of ferromagnetic/non-magnetic/ferromagnetic metal junction [19]. Under steady state nonequilibrium conditions, a magnetization dipole layer much larger than the charge dipole layer is induced at the interface while the magnetization dipole layer is zero under equilibrium conditions. We have applied this idea to the double FIS junction [18].

We now ask the question: How do co-ordinations between the Rashba spin-orbital interaction and the space charge affect the spin transport in the double FIS junction? It was known that the Coulomb interaction may enhance the Rashba effect. In a one-dimensional Luttinger liquid formalism, Hauser has reported an enhancement of the Rashba effect due to the spin charge separation [20]. Such an enhancement was also found in a two-dimensional electron gas system [21]. However, the effect of the Rashba spin-orbital interaction in the diffusion region was thought to be not important. In this work, we would like to investigate the co-ordination between the Rashba spin-orbital interaction and the space charge effect in the double FIS junction in the nonequilibrium transport process. To completely solve the nonequilibrium problem with interactions is highly non-trivial. It requires solving self consistently Boltzmann type spin transport equation with the Poisson equation. What we want to touch in this work is using a simple Hartree approximation to check if the effect comes from these interactions is significant. Consequently, it is found that if (i) the resistance of the tunneling barrier is comparable to the semiconductor resistance and (ii) the n-type semiconductor has an appropriate doping, then while the magnetoresistance of the junction is greatly enhanced as the charge screening length becomes shorter as we already showed in [18], it is grown up as the Rashba spin-orbital coupling. The shorter charge screening length is , the more gain in the magnetoresistance comes from the Rashba term. Comparing with the non-interacting model where the Rashba effect may not be observed in the diffusion region, we see a great increment of the magnetoresistance comes from the co-ordination between the Rashba spin-orbital interaction and space charge effect.

Rashba Spin-Orbital Coupling: We consider a two-dimensional electron gas in a narrow gap quantum well, such as those based on InAs. The spin-orbital coupling in this kind of systems is dominated by Rashba term [22]:

\[ H_{so} = \alpha (\sigma_x p_y - \sigma_y p_x), \]

where \(\sigma_{x,y}\) are the Pauli matrices and the Rashba param-
eter $\alpha$ is determined by the asymmetry of the potential confining the electrons in the two-dimensional $x$-$y$ plane and can be controlled by a gate voltage [3]. For the system we are considering, its value is about $10^{-12} - 10^{-11}$ eVm [23]. For a double FIS junction where the current flows in the $x$-direction, we can estimate the spin dependence of the density of state and the resistance of the electron gas. According to the Rashba term (1), the single particle dispersion reads

$$E_s = \frac{p^2 k^2}{2m^*} + \sigma \alpha k_s,$$  \hspace{1cm} (2)

where $m^* \approx 0.04m_e$ for the bare electron mass $m_e$ and $k_s = k + \sigma \frac{m^*}{h^2} \alpha$; $\sigma$ is called spin-orbital coupling label [24]. The Rashba spin-orbital interaction contributes a current $j_{so}$ to the system. However, in the diffusion region, such an effect may be small [24]. Here, we would like to see another effect arising from the Rashba term. When the Rashba term is non-zero, it is easy to see the density of state.

Typically, $\alpha$ is given by [24]

$$N_s^N = N_F^N (1 + \alpha_N),$$  \hspace{1cm} (3)

where $N_s^N$ is the density of state at the Fermi surface of the semiconductor for $\alpha = 0$ and $\alpha_N = \frac{\alpha}{v_F}$ for the Fermi velocity $v_F$. It is seen that the density of state is not $\sigma$-dependent [24]. For a typical two-dimensional electron gas, the electron density is of order $\rho_s = 10^{11}$ and $10^{12}$ cm$^{-2}$. Thus, using $v_F = \frac{k_F}{m^*} = \frac{\hbar}{m^*} \sqrt{2\pi \rho_e}$, $\alpha_N$ is in order of $10^{-2}$ and $10^{-3}$. In the following, we will see that the magnetoresistance of the double FIS junction is very sensitive to the change of the charge screening length which is determined by the density of state.

**Description of the Junction:** In the diffusion region and the room temperature, we consider the junction F1-I1-S-I2-F2 along the $x$-direction. The thickness of the metal (F1, F2), the insulating barriers (I1, I2) and the semiconductor (S) are denoted by $L_{j,L}, d_{1,2}$ and $x_0$, respectively (See, Figure 1). For the practical case, $x_0$ is less than the spin diffusion length $l_N$ of the two-dimensional electron gas in the semiconductor. The charge screening lengths in the metal and the semiconductor are denoted by $\lambda_{L,R}$ and $\lambda_N$, respectively. In our model, we assume $\lambda_N \ll l_N$ and $\lambda_{R,L} \ll l_{R,L}$, the spin diffusion lengths in the metal. Typically, $\lambda \sim 10^{-4}$ nm, $l \sim 10^4$ nm, and $l_N > 1$ um. $x_0 \sim 100$ nm to 1 um, depending on the structure of junctions. The screening length in the semiconductor, $\lambda_N$, is dependent on the doping of the semiconductor and can vary in a wide range, say 10nm for the heavy doped semiconductor and 100nm-1um for the lightly doped or undoped semiconductor. To avoid discussing the spin-orbit splitting of the heavy and the light-holed bands near the zone center, we consider the $n$-type semiconductor only.

The problem we would like to solve has been defined in [19,18]. Summarily, it is four sets of equations:

1. The total charge-current conservation is described by

$$\nabla \cdot j = -\frac{\partial \rho}{\partial t},$$  \hspace{1cm} (4)

where $\rho$ is the charge density.

2. The spin $s$-dependent current is determined by the diffusion equations. In order to allow an analytic analysis, we take a simple Hartree approximation into account to see the space charge effect. Under such an approximation, the diffusion equations reads [19]

$$j_s = \sigma_s (\nabla \mu_s - \nabla W_0 + E),$$  \hspace{1cm} (5)

where the magnitude of the electric charge has been set as one; $E$ is the external electric field; the chemical potential $\mu_s$ is related to the charge density $\rho_s$ by $\nabla \mu_s = \frac{\rho_s}{\rho_s}$ for the spin-dependent density of state. $W_0 = \int d\vec{r} U_{int}(\vec{r},\vec{r})\rho(\vec{r})$ is the potential caused by the screened Coulomb interaction $U_{int}(\vec{r})$ and $\nabla W_0$ is the so-called screening field induced by $U_{int}(\vec{r})$.

3. The third is the magnetization relaxation equation where the magnetization density $M = \rho_l - \rho_1$ relaxes with a renormalized spin diffusion length $l$. In the relaxation time approximation, one has

$$\nabla^2 M = M/l^2 = 0.$$  \hspace{1cm} (6)

4. The boundary conditions at the interfaces are given by

$$\Delta \mu_s - \Delta W = r(1-s\gamma)j_s,$$  \hspace{1cm} (7)

where $\Delta \mu_s = \mu_s + Ex$; $Ex$ is the voltage drop on the left side of the barrier and $\Delta W$ is the electric potential drop across the barrier, which is assumed much smaller than $\Delta \mu_s$; $r = r(1-s\gamma)$ is the barrier resistance. We assume that there is no spin relaxation in the insulator, the spin-dependent currents are continuous across the junctions, $j_s^L(-d_1/2) = j_s^N(d_1/2)$ and $j_s^R(x_0 + d_2/2) = j_s^N(x_0 - d_2/2)$.

In addition, we have the neutrality condition for the total charges ($Q_{L,N,R}$, e.g., $Q_N = \int_{d_1/2}^{x_0 + d_1/2} \rho dx$) accumulated at the interfaces. By Gauss’ law, for the point $d_1/2 < x < x_0 + d_1/2$, i.e., inside the semiconductor, the potential $W_0$ is determined by

$$\nabla W_0(x) = 4\pi Q_L + 4\pi \int_{d_1/2}^{x} \rho dx,$$  \hspace{1cm} (8)

whose constant part of the right hand side gives the constraint on the charge while the $x$-dependent part gives the function form of the potential $W_0$. Another constraint is the neutrality of the system:

$$Q_L + Q_N + Q_R = 0,$$  \hspace{1cm} (9)

With those sets of equations (Eqs.(4)-(7)) and the two constraint on the charges (Eqs.(8) and (9)), the problem can be solved. The formal solutions of the problem are
\[ \rho^L(x) = \frac{\lambda_L}{l_L} \rho_{10}^L e^{(x+d_1/2)/\lambda_L} + \frac{\lambda^2}{l_L^2} \rho_{20}^L e^{(x+d_2/2)/l_L}, \]
\[ M^L(x) = M_0^L (1 - \frac{\lambda^2}{l_L^2} e^{(x+d_2/2)/l_L}), \]
(10)

with similar solutions for the right hand side. In the semiconductor, if \( \lambda_N \ll x_0 \),
\[ \rho^N(x) = \rho^{(1)}N(x) + \rho^{(2)}N(x), \]
\[ \rho^{(1)}N(x) = \frac{\lambda_N}{l_N} \rho_{10}^N e^{-(x-d_1/2)/\lambda_N} + \frac{\lambda^2}{l_N^2} \rho_{20}^N e^{-(x-d_1/2)/l_N}, \]
\[ \rho^{(2)}N(x) = \frac{\lambda_N}{l_N} \rho_{10}^N e^{-(x-x_0+d_2/2)/\lambda_N} + \frac{\lambda^2}{l_N^2} \rho_{20}^N e^{-(x-x_0+d_2/2)/l_N}. \]
(11)

\( M^{(1,2)} \) can be obtained similarly. All of coefficients in (10) and (11) can be determined by using Eqs.(4)-(7) and the constraint (8) and (9). The screening potential \( W_0 \) is determined by Gauss' law. The total current is \( j = \sum_j j_j \). Although \( j_j \) are not a constant, the total current \( j \) is still a constant.

The spin-dependent currents: It is necessary to simplify the problem to demonstrate the essential physics. One sets the parameters of the metals and barrier widths on the left and right sides to be the same: \( \lambda_R = \lambda_L = \lambda \), \( l_L = 1_R = l \), \( d_1 = d_2 = d \) and so on. The resistances of the barrier layers are taken as \( r^{(1)} = r^{(2)} = r \); \( \gamma_1 = \gamma_2 = \gamma \) for the parallel configuration and \( \gamma_1 = -\gamma_2 = \gamma \) for the anti-parallel configuration. To illustrate, we focus on the calculation in the left barrier located at \( x = 0 \). The tunneling resistance is given by
\[ r_s^{(1)} = r(1 - \gamma s) = r_0_s e^{d(\kappa_s(\mu) - \kappa_s(0))}, \]
(12)
where \( \kappa_s(\mu) \propto \int_0^d dx [2m(U - \Delta \mu_s(0) x/d)]^{1/2} \), with \( U \) the barrier height. The current \( j_s^L(x) \) at \( x = 0 \) is dependent on the bias voltage and the interaction, which is given by
\[ j_s^L(0) = A_s j_0s, \]
(13)
where, for the ferromagnet metal on left hand side,
\[ A_s = 1 + \frac{4\pi\lambda^2}{l} \alpha(\beta - \rho_{10}^L + M_0^L) \]
(14)
and \( j_0s = \sigma_s E \) is the current with no interaction and the current \( j_{0s} \) that is contributed to from the Rashba term has been neglected; \( \beta(\alpha) \) measures the spin asymmetry of the conductivities \( \sigma_s \) (densities of states at the Fermi surface \( N_s \)): \( \sigma_s = \frac{e^2}{2}(1 + \beta s) \) and \( N_s = \frac{1}{2} N_F (1 + \alpha s) \) where \( N_F \) is related to the screening length \( \lambda \) by \( \frac{1}{N_F} = 2\pi\lambda^2 \frac{\rho_{10}^L}{e^2}. \) Noting that both \( \rho_{10}^L \) and \( M_0^L \) are proportional to the external electric field \( E \), \( A_s \) is solely determined by the material parameters.

Eq. (13) implies that the spin-dependent current \( j_s(0) \) passing the interface differs a factor \( A_s \) from the non-interacting current \( j_{0s}(0) \). For the parallel configuration, \( j_{0s}(0) \) is given by [18]
\[ j_{0s}^r(0) \approx \frac{V}{R_N^s + 2r_0_s Y_s(0)}, \]
(15)
where \( Y_s(0) = e^{\kappa_s(d/\lambda)^2 - (1-\Delta \mu_s(0)\rho_{10}^L)} \) and \( R_N^s = R_N^s(1 - \beta N) \) with \( \beta N \approx \alpha N \). For the anti-parallel configuration,
\[ j_{0s}^r(0) \approx \frac{V}{R_N^s + \sum_s r_{0s} Y_s(0)}. \]
(16)
The magnetoresistance: Since the total current is constant everywhere, we have, for the parallel configuration \( R_{AP} = \sum_s j_s(0)/V \) and for the anti-parallel configuration, \( R_{AP} = \sum_s j_s(0)/V \). From these, we obtain the magnetoresistance ratio
\[ \frac{\Delta R}{R} = \frac{R_{AP} - R_P}{(R_{AP} + R_P)} = \frac{X}{2 + X}, \]
(17)
where \( X = \sum_s A_s^P \frac{R_{AP}^s + \sum_s r_{0s} Y_s(0)}{2(R_{AP}^s + 2r_{0s} Y_s(0))} - 1 \). For non-interacting electrons, \( A_s^P = A_s^P = 1 \) and we know that that \( \Delta R/R \) will not be beyond a maximal value at \( V \to 0 \) about 3.2% for \( r_{0+} : r_{0-} : R_{AP} = 1 : 2 : 1 \) and decays as the bias voltage increases [18]. Since \( j_{0s} \) has been neglected, there is no observable Rashba effect without interactions. After the interaction is included, the ratio (17) grows greatly and the Rashba effect is enhanced as \( \lambda_N \) becomes smaller. This can be clearly seen in Figs. 2 and 3. We take \( x_0 = 1.25 \mu m, \lambda = 0.1 \mu m, l = 20 \mu m, \) and \( l_N = 3 \mu m \) and set \( \alpha = \beta = 1/2 \). The different choice of \( \alpha \) and \( \beta \) will not qualitatively affect the result if they do not deviate from \( 1/2 \) too much. In Fig. 2, we depict the magnetoresistance versus the bias voltage for \( \lambda_N = 100 \mu m \) with \( \alpha N \) from 0 to 0.05. It is seen that \( \Delta R/R \) raises from 16% to 18% when \( \alpha N \) from 0 to 0.05. In Fig. 3, for \( \lambda_N = 50 \mu m \), it is shown that the Rashba effect lifts much faster. \( \Delta R/R \) raises from 25% to 30% for \( \alpha N \) from 0 to 0.05. Hence, we see a strong co-ordination between the Rashba spin-orbital and the screened Coulomb interactions to increase the magnetoresistance. While the Coulomb interaction largely enhances the magnetoresistance, the Rashba spin-orbital interaction may enhance \( \Delta R/R \). This kind of Rashba effect becomes more significant in a shorter charge screening length.

In conclusions, we have shown the co-ordination between the Rashba spin-orbital and screened Coulomb interactions on electron injection from ferromagnet to semiconductor. The magnetoresistance grows fast as the charge screened length in the semiconductor becomes shorter. The Rashba term also enhances the magnetoresistance and plays more important role as the Coulomb interaction is stronger. In fact, by a close examination
to our solution, this Rashba effect is corresponding to a renormalization to the screening length \( \lambda_N \rightarrow \frac{\lambda_N}{1 + \alpha_N} \) in the dominate terms of the solution. Because our solution is very sensitive to \( \lambda_N \), it is understood that why a small spin-orbital coupling can cause a relative large gain in the magnetoresistance.

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