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Co-ordination between the Rashba spin–orbital interaction and space charge effect and enhanced spin injection into semiconductors in the diffusion region

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Abstract

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 the diffusion region, if the resistance of the tunnelling 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 the screened Coulomb interaction in non-equilibrium transport processes within the Hartree approximation.

1. Introduction

Spintronics is interesting since it involves the 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 focuses in spintronics lies in injecting spin polarized electrons into non-magnetic semiconductors [4–10]. This is partially motivated by the high magnetoresistance observed in ferromagnet tunnel junctions [11]. However, in the diffusion region and at room temperature, experiments have so far observed a small magnetoresistance ratio of 1% [12, 13] in ferromagnet/semiconductor/ferromagnet structures. Rashba proposed a ferromagnetic metal/tunnelling-insulator/semiconductor (FIS) junction to improve the spin injection rate [14]. Many different geometries of the tunnelling junction are discussed in [15]. It is possible to increase the magnetoresistance to almost 10% using a very large electric field [16].

The effect of the Rashba spin–orbital interaction on spin injection has recently become an interesting research issue. The additional quantum interference effect between two spin components due to Rashba coupling has been studied in the quantum coherence region and the difference in conductance dependent on the junction length between parallel and anti-parallel magnetic configurations has been pointed out [9]. Since the electron spin s is no longer a good quantum number when Rashba spin–orbital coupling becomes important, the spin–orbital-induced spin accumulation and the conditions for its observability have been a matter of controversy even in the diffusion region [17, 18]. Inoue *et al* [18] dealt with the spin accumulation and the conductivity tensor on an equal footing from a microscopic point of view. They found that the electron density of states is enhanced by the spin accumulation induced by Rashba spin–orbital coupling. However, it is easy to check that, even if the sample quantity can be improved such that the electron density may be as low as 10^9 cm^{-2} in InAs, this correction to the conductivity is only about 1%. We shall neglect this spin accumulation effect to the conductivity due to Rashba precession in the present work. Besides the quadratic correction to the conductivity, Inoue *et al* [18] also mentioned the possible influence of the Rashba effect on spin transport within the two-dimensional electron gas for a F/S/F junction in the diffusion regime. Further careful analysis is required but this is beyond the goal of this present work. The increase in the density of states affects not only the conductivity but also many physical observables. In this work, we shall concentrate on the effect of such an increase on the screened Coulomb interaction and then the magnetoresistance of a double FIS junction.

In recent work [19], we investigated the space charge effect in the non-equilibrium 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 non-equilibrium transport process was first found to play an important role in the characteristics of the ferromagnetic/non-magnetic/ferromagnetic metal junction device [20]. Under steady state non-equilibrium 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 [19].

We now ask the question: how do co-ordinations between the Rashba spin–orbital interaction and the space charge affect 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, Haüsler has reported an enhancement of the Rashba effect due to spin charge separation [21]. Such an enhancement was also found in a two-dimensional electron gas system [22].

In this work, we would like to investigate the co-ordination between the Rashba spin–orbital interaction (due to this increase in the density of states) and the space charge effect in the double FIS junction in the non-equilibrium transport process. We focus on the diffusion region, i.e. the junction length is much longer than the mean free path of the electron. To completely solve the non-equilibrium problem with interactions is highly non-trivial. It requires solving self-consistently a Boltzmann-type spin transport equation with the Poisson equation. What we want to describe in this work is using a simple Hartree approximation to check if the effect coming from these interactions is significant. Consequently, it is found that if (i) the resistance of the tunnelling 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 have already shown in [19], it is increased as the Rashba spin–orbital coupling increases. This increase is marked if the electron density in the sample reaches $\sim 10^9$ cm^{-2}. The shorter the charge screening length is, the more the gain in the magnetoresistance comes from the Rashba term. Comparing with the non-interacting model, we see a large part of the increase in the magnetoresistance comes from the co-ordination between the Rashba spin–orbital interaction and the space charge effect.

2. 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 system is dominated by the Rashba term [23]:

$$H_{\mathrm{so}} = \alpha(\sigma_x p_y - \sigma_y p_x), \tag{1}$$

where $\sigma_{x,y}$ are the Pauli matrices and the Rashba parameter α 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} eV m [24]. For a double FIS junction, where the current flows in the x direction, we can estimate the spin dependence of the density of states and the resistance of the electron gas. According to the Rashba term (1), the single-particle dispersion is

$$E_\sigma = \frac{\hbar^2 k_\sigma^2}{2m^*} + \sigma\alpha k_\sigma, \tag{2}$$

where $m^* \approx 0.04\, m_{\mathrm{e}}$ for the bare electron mass m_{e} and $k_\sigma = k + \sigma\frac{m^*\alpha}{\hbar^2}$: σ is the spin–orbital coupling label. This means that the electron spin s is no longer a good quantum number and the spin–orbital-induced spin accumulation and the conditions for its observability have become a matter of controversy [17, 18]. The Rashba spin–orbital interaction contributes a current operator $\hat{j}_{\mathrm{so}}$ to the system:

$$\hat{j}_{\mathrm{so},x} = -\frac{e\alpha}{\hbar}\sigma_y, \qquad \hat{j}_{\mathrm{so},y} = \frac{e\alpha}{\hbar}\sigma_x. \tag{3}$$

It has been shown that, in the diffusion region, the Rashba term contributes an α quadratic term to increase the current or conductivity due to spin accumulation [18]:

$$\begin{aligned} j_x &= \langle \hat{j}_x \rangle = \sigma_{xx} E, \\ \sigma_{xx} &= \frac{2e^2\rho_{\mathrm{e}}\tau}{m^*}(1 + \delta_{\mathrm{N}}), \end{aligned} \tag{4}$$

where $\delta_{\mathrm{N}} = (\frac{\alpha}{\hbar v_{\mathrm{F}}})^2$ with $v_{\mathrm{F}} = \frac{k_{\mathrm{F}}}{m^*} = \frac{\hbar}{m^*}\sqrt{2\pi\rho_{\mathrm{e}}}$ the Fermi velocity. For a two-dimensional electron gas on an InAs base, the electron density varies from $\rho_{\mathrm{e}} = 10^{11}$ to 10^{12} cm^{-2} in the present existing samples and δ_{N} is of the order of 10^{-4} to 10^{-5}. It is expected that the electron density may increase to 10^9 cm^{-2} and $\delta_{\mathrm{N}} \sim 10^{-2}$. Even so, we can still neglect such a spin accumulation and regard the original electron spin s as a good quantum number. However, in this paper, we would like to look at another effect arising from the Rashba term. Notice that equation (4) may yield a renormalization of the density of states at the Fermi surface:

$$N_{\mathrm{N}}^{\mathrm{so}} = N_{\mathrm{F}}^{\mathrm{N}}(1 + \delta_{\mathrm{N}}), \tag{5}$$

where $N_{\mathrm{F}}^{\mathrm{N}} = \frac{L}{2\pi}\frac{1}{\hbar v_{\mathrm{F}}}$ is the density of states at the Fermi surface of the semiconductor, which is σ (or s)-independent [18, 25]. Thus, the spin polarized conductivity is also independent of the spin [18]:

$$\begin{aligned} \sigma_{xx}^{\uparrow} &= \sigma_{xx}^{\downarrow}, \\ j_{x\uparrow} &= j_{x\downarrow}, \end{aligned} \tag{6}$$

for $\sigma_{xx} = \sigma_{xx}^{+} + \sigma_{xx}^{-} = \sigma_{xx}^{\uparrow} + \sigma_{xx}^{\downarrow}$ and $j_x = j_{x\uparrow} + j_{x\downarrow}$. Hence, for a single junction, the Rashba precession does not affect the spin-dependent transport in the diffusion region except

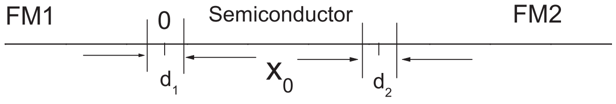

Figure 1. A sketch of the double FIS junction.

that the conductivity has a quadratic correction. For a double F/S/F junction, there may be the influence of Rashba precession when the spin configurations of two ferromagnets lie either parallel or anti-parallel [18]. For this aspect, more analysis is required. In the following, however, we do not go into this issue and we will discuss another matter due to the co-ordination between Rashba precession and the screened Coulomb interaction. We will see that the magnetoresistance of the double FIS junction is very sensitive to the change in the charge screening length, which is determined by the density of states. When δ_N is of the order of 10^{-2}, there will arise a remarkable observed effect from the increase of the density of states due to Rashba spin–orbital coupling.

3. Description of the junction

In the diffusion region and at room temperature, we consider the junction F1–I1–S–I2–F2 in the x direction. The thickness of the metal (F1, F2), the insulating barriers (I1, I2) and the semiconductor (S) are denoted by $L^{\mathrm{L,R}}$, $d_{1,2}$ 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 $\lambda_{\mathrm{L,R}}$ and λ_N, respectively. In our model, we assume $\lambda_N \ll l_N$ and $\lambda_{\mathrm{R,L}} \ll l_{\mathrm{R,L}}$, the spin diffusion lengths in the metal. Typically, $\lambda \sim 10^{-1}$ nm, $l \sim 10^1$ nm and $l_N > 1\ \mu$m. $x_0 \sim 100$ nm to 1 μm, depending on the structure of the junctions. The screening length in the semiconductor, λ_N, is dependent on the doping of the semiconductor and can vary over a wide range, say about 10 nm for the heavily doped semiconductor and 100 nm to 1 μm for the lightly doped or undoped semiconductor. To avoid discussing the spin–orbit splitting of the heavy and light hole bands near the zone centre, we consider the n-type semiconductor only.

The problem we would like to solve has been defined in [19, 20]. Briefly, it consists of four sets of equations:

(1) The total charge–current conservation is described by

$$\nabla \cdot \mathbf{j} = -\frac{\partial \rho}{\partial t}, \tag{7}$$

where ρ is the charge density.

(2) According to our approximation, the electron spin is an approximately good quantum number. The spin s-dependent current is determined by the diffusion equations. In order to allow for an analytical analysis, we take a simple Hartree approximation into account to see the space charge effect. Under such an approximation, the diffusion equations are [20]

$$j_s = \sigma_s(\nabla \mu_s - \nabla W_0 + E), \tag{8}$$

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

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

$$\nabla^2 M - M/l^2 = 0. \tag{9}$$

(4) The boundary conditions at the interfaces are given by

$$\Delta\tilde{\mu}_s - \Delta W = r(1 - s\gamma) j_s, \tag{10}$$

where $\tilde{\mu}_s = \mu_s + Ex$, Ex is the voltage drop on the left side of the barrier, ΔW is the electric potential drop across the barrier, which is assumed to be much smaller than $\Delta\mu_s$, and $r_s = r(1 - s\gamma)$ is the barrier resistance. We assume that there is no spin relaxation in the insulator and that the spin-dependent currents are continuous across the junctions, $j_s^{\mathrm{L}}(-d_1/2) = j_s^{\mathrm{N}}(d_1/2)$ and $j_s^{\mathrm{R}}(x_0 + d_2/2) = j_s^{\mathrm{N}}(x_0 - d_2/2)$. The resistance of the insulator layer can then be estimated by the transmission probability of the barrier (see below, equation (15)).

In addition, we have the neutrality condition for the total charges ($Q_{\mathrm{L,N,R}}$, e.g. $Q_{\mathrm{N}} = \int_{d_1/2}^{x_0+d_1/2} \rho\,\mathrm{d}x$) accumulated at the interfaces. By Gauss's 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

$$\nabla W_0(x) = 4\pi Q_{\mathrm{L}} + 4\pi \int_{d_1/2}^{x} \rho\,\mathrm{d}x, \tag{11}$$

whose constant part on 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:

$$Q_{\mathrm{L}} + Q_{\mathrm{N}} + Q_{\mathrm{R}} = 0. \tag{12}$$

With these sets of equations (equations (7)–(10)) and the two constraints on the charges (equations (11) and (12)), the problem can be solved. The formal solutions of the problem are

$$\begin{aligned} \rho^{\mathrm{L}}(x) &= \frac{\lambda_{\mathrm{L}}}{l_{\mathrm{L}}}\rho_{10}^{\mathrm{L}}\mathrm{e}^{(x+d_1/2)/\lambda_{\mathrm{L}}} + \frac{\lambda_{\mathrm{L}}^2}{l_{\mathrm{L}}^2}\rho_{20}^{\mathrm{L}}\mathrm{e}^{(x+d_1/2)/l_{\mathrm{L}}}, \\ M^{\mathrm{L}}(x) &= M_0^{\mathrm{L}}\left(1 - \frac{\lambda_{\mathrm{L}}^2}{l_{\mathrm{L}}^2}\right)\mathrm{e}^{(x+d_1/2)/l_{\mathrm{L}}}, \end{aligned} \tag{13}$$

with similar solutions for the right-hand side. In the semiconductor, if $\lambda_{\mathrm{N}} \ll x_0$,

$$\begin{aligned} \rho^{\mathrm{N}}(x) &= \rho^{(1)}(x) + \rho^{(2)}(x), \\ \rho^{(1)}(x) &= \frac{\lambda_{\mathrm{N}}}{l_{\mathrm{N}}}\rho_{10}^{(1)}\mathrm{e}^{-(x-d_1/2)/\lambda_{\mathrm{N}}} + \frac{\lambda_{\mathrm{N}}^2}{l_{\mathrm{N}}^2}\rho_{20}^{(1)}\mathrm{e}^{-(x-d_1/2)/l_{\mathrm{N}}}, \\ \rho^{(2)}(x) &= \frac{\lambda_{\mathrm{N}}}{l_{\mathrm{N}}}\rho_{10}^{(2)}\mathrm{e}^{(x-x_0+d_2/2)/\lambda_{\mathrm{N}}} + \frac{\lambda_{\mathrm{N}}^2}{l_{\mathrm{N}}^2}\rho_{20}^{(2)}\mathrm{e}^{(x-x_0+d_2/2)/l_{\mathrm{N}}}. \end{aligned} \tag{14}$$

$M^{(1),(2)}$ can be obtained similarly. All of the coefficients in (13) and (14) can be determined by using equations (7)–(10) and the constraints (11) and (12). The screening potential W_0 is determined by Gauss's law. The total current is $j = \sum_s j_s$. Although j_s is not a constant, the total current j is still a constant.

4. The spin-dependent currents

It is necessary to simplify the problem to demonstrate the essential physics. One sets the parameters of the metals and the barrier widths on the left and right sides to be the same: $\lambda_{\mathrm{R}} = \lambda_{\mathrm{L}} = \lambda$, $l_{\mathrm{L}} = l_{\mathrm{R}} = l$, $d_1 = d_2 = d$ 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 this, we focus on the calculation on the left barrier located at $x = 0$. From the transmission probability through the barrier, the tunnelling resistance is given by

$$r_s^{(1)} = r(1 - \gamma s) = r_{0,s} \exp[d(\kappa_s(\mu) - \kappa_s(0))], \tag{15}$$

where $\kappa_s(\mu) \propto \int_0^d \mathrm{d}x\, [2m(U - \Delta\mu_s(0)x/d)]^{1/2}$, with U the barrier height. The current $j_s^{\mathrm{L}}(x)$ at $x = 0$ is dependent on the bias voltage and the interaction, which is given by

$$j_s^{\mathrm{L}}(0) = A_s j_{0s}, \tag{16}$$

where for the ferromagnetic metal on the left-hand side

$$A_s = 1 + \frac{4\pi\lambda^2}{l} \frac{\delta(\beta - s)}{1 - \delta\beta} \frac{\rho_{10}^{\mathrm{L}} + M_0^{\mathrm{L}}}{E}. \tag{17}$$

$j_{0s} = \sigma_s E$ is the current with no interaction and the current j_{so} that is contributed from the Rashba term has been neglected. β (δ) measures the spin asymmetry of the conductivities σ_s (the densities of states at the Fermi surface N_s): $\sigma_s = \frac{\sigma}{2}(1 + \beta s)$ and $N_s = \frac{1}{2} N_{\mathrm{F}}(1 + s\delta)$, where N_{F} is related to the screening length λ by $\frac{1}{N_{\mathrm{F}}} = 2\pi\lambda^2 \frac{1-\delta^2}{1-\delta\beta}$. Noting that both ρ_{10}^{L} and M_0^{L} are proportional to the external electric field E, A_s is solely determined by the material parameters.

Equation (16) implies that the spin-dependent current $j_s(0)$ passing through the interface differs by a factor A_s from the non-interacting current $j_{0s}(0)$. For the parallel configuration, $j_{0s}(0)$ is given by [19]

$$j_{0s}^{\mathrm{p}}(0) \approx \frac{V}{R_{\mathrm{N}}^{\mathrm{so}} + 2r_{0,s} Y_s(0)}, \tag{18}$$

where $Y_s(0) = \mathrm{e}^{\kappa_{0s} d [\frac{2}{3\Delta\hat{\mu}_s(0)}(1 - (1 - \Delta\hat{\mu}_s(0))^{3/2}) - 1]}$ and $R_{\mathrm{N}}^{\mathrm{so}} = R_{\mathrm{N}}(1 - \beta_{\mathrm{N}})$ with $\beta_{\mathrm{N}} \approx \delta_{\mathrm{N}}$. For the anti-parallel configuration

$$j_{0s}^{\mathrm{a}}(0) \approx \frac{V}{R_{\mathrm{N}}^{\mathrm{so}} + \sum_s r_{0,s} Y_s(0)}. \tag{19}$$

5. The magnetoresistance

Since the total current is constant everywhere, we have, for the parallel configuration $\frac{1}{R_{\mathrm{P}}} = \sum_s j_s(0)/V$ and for the anti-parallel configuration $\frac{1}{R_{\mathrm{AP}}} = \sum_s j_s(0)/V$. From these, we obtain the magnetoresistance ratio:

$$\frac{\Delta R}{R} \equiv \frac{R_{\mathrm{AP}} - R_{\mathrm{P}}}{(R_{\mathrm{AP}} + R_{\mathrm{P}})} = \frac{X}{2 + X}, \tag{20}$$

where

$$X = \sum_s \frac{A_s^{\mathrm{P}}(R_{\mathrm{N}}^{\mathrm{so}} + \sum_{s'} r_{0,s'} Y_{s'}^{\mathrm{AP}}(0))}{2(R_{\mathrm{N}}^{\mathrm{so}} + 2r_{0,s} Y_s^{\mathrm{P}}(0))} - 1.$$

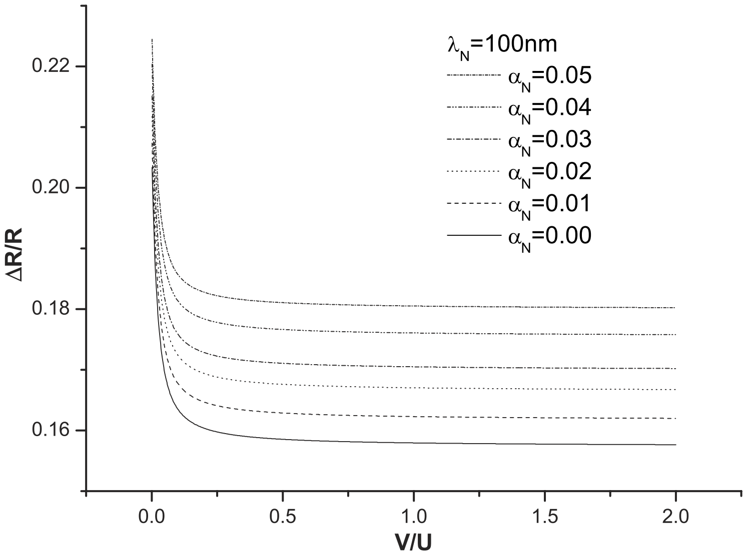

Figure 2. The magnetoresistance versus the bias voltage (in units of U) with $\lambda_N = 100$ nm. The junction parameters are $x_0 = 1.25\ \mu$m, $\lambda = 0.1$ nm, $l = 20$ nm and $l_N = 3\ \mu$m. Three different values of δ_N are taken.

For non-interacting electrons, $A_+^P = A_-^P = 1$ and we know that $\Delta R/R$ will not be beyond a maximal value (at $V \to 0$) of about 3.2% for r_{0+}:r_{0-}:R_N = 1:2:1 and decays as the bias voltage increases [19]. Since j_{so} has been neglected, there is no observable Rashba effect without interactions. After the interaction is included, the ratio (20) increases greatly and the Rashba effect is enhanced as λ_N becomes smaller. To see this effect, we assume the electron density is of the order of 10^9 cm^{-2} and $\delta_N \sim 10^{-2}$. In this region, this effect from the Rashba term can be clearly seen in figures 2 and 3. We take $x_0 = 1.25\ \mu$m,[3] $\lambda = 0.1$ nm, $l = 20$ nm and $l_N = 3\ \mu$m and set $\delta = \beta = 1/2$. The different choices of δ and β will not qualitatively affect the result if they do not deviate from 1/2 too much. In figure 2, we depict the magnetoresistance versus the bias voltage for $\lambda_N = 100$ nm with δ_N varying from 0 to 0.05. It is seen that $\Delta R/R$ increases from 16% to 18% when δ_N increases from 0 to 0.05. In figure 3, for $\lambda_N = 50$ nm, it is shown that the Rashba effect increases much faster. $\Delta R/R$ increases from 25% to 30% for δ_N going from 0 to 0.05. Hence, we see a strong co-ordination between the Rashba spin–orbital and screened Coulomb interactions in increasing 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 for a shorter charge screening length. In figure 4, we depict the enhancement of $\Delta R/R$ as δ_N. An almost linear relation between the magnetoresistance and δ_N is found for given values of λ_N and U/V. The slope is steeper as λ_N becomes shorter. Notice that, if we consider the electron density to be 10^{11} cm^{-2}, this effect is still very small. Thus, to verify our prediction, the sample quantity has to be improved in experiments.

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[3] For $T \sim 1$ K, the mean free path of the two-dimensional electron gas may be of the order of 1 μm for GaAs with the electron density 10^{10} cm^{-2}. However, at room temperature, this mean free path may be lowered by one or two orders. On the other hand, since the relevant electron density is 10^9 cm^{-2} in the present work and the electron mobility in InAs is lower, the mean free path of the electron in our system is much shorter than 1 μm.

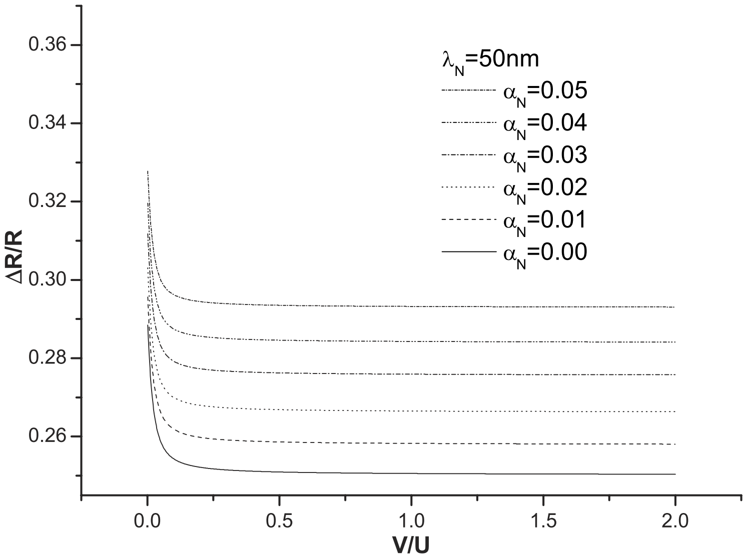

Figure 3. The magnetoresistance versus the bias voltage with $\lambda_N = 50$ nm. Other parameters are the same as those in figure 2.

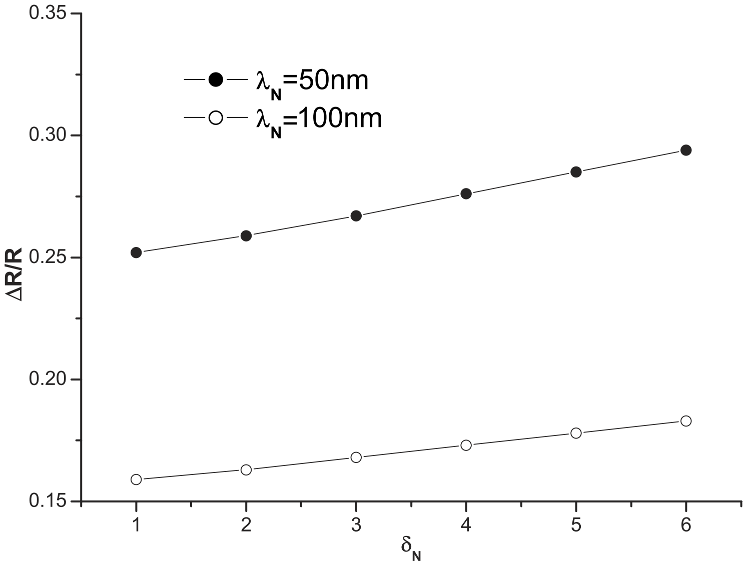

Figure 4. The magnetoresistance versus δ_N with respect to $U/V = 0.25$.

6. Conclusions

We have shown the co-ordination between the Rashba spin–orbital and screened Coulomb interactions on electron injection from a ferromagnet to a semiconductor in the diffusion region. The magnetoresistance increases rapidly as the charge screened length in the semiconductor becomes shorter. If the electron density in the sample is low enough, the Rashba term can also enhance the magnetoresistance and plays a more important role when the Coulomb interaction is stronger. In fact, by a close examination of our solution, this Rashba effect corresponds to a renormalization of the screening length $\lambda_N \rightarrow \lambda_N^* = \lambda_N/(1+\delta_N)$ in the dominant terms of the solution. Because our solution is very sensitive to λ_N, it is understood why a small spin–orbital coupling can cause a relative large increase in the magnetoresistance.

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