Voltage-controlled spin precession in InAs quantum wells

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Abstract
In this work we investigate spin diffusion in InAs quantum wells with the Rashba spin–orbit coupling modulated by a gate voltage. The gate-voltage dependence of spin diffusion under different temperatures is studied with all the scattering explicitly included. Our result partially supports the claim of the realization of the Datta–Das spin-injected field effect transistor by Koo et al. (2009 Science 325 1515). We also show that the scattering plays an important role in spin diffusion in such a system.

(Some figures in this article are in colour only in the electronic version)

In the past decades, a great deal of effort has been made towards the realization of the spintronic devices [1–4]. The spin-injected field-effect transistor (SIFET), proposed by Datta and Das in 1990 [5], is one of the most intriguing devices [6–8] but posts some challenges to experiments (e.g., the spin-polarized injection and detection). Very recently Koo et al. [9] reported that, in InAs quantum wells with nonlocal spin valve configuration, the nonlocal voltage was observed to oscillate with the variation of gate voltage at low temperature when the two ferromagnetic (FM) electrodes (spin injector and detector) are magnetized along the spin-diffusion direction. They claimed that they have realized the SIFET because the oscillation can be fitted by a theoretical equation describing the SIFET. Nevertheless, as pointed out by Bandyopadhyay [10], the theoretical equation adopted by Koo et al only applies to the one-dimensional system instead of the two-dimensional one. Therefore, the agreement between this equation and the experimental data [9] makes little sense and doubt is cast on the conclusion presented by Koo et al. Later, Zainuddin et al. [11] extended the one-dimensional theory to the two-dimensional case with an equation similar to the one obtained from the one-dimensional theory. However, as further reported by Agnihotri and Bandyopadhyay [12], the experimental data actually do not match the equation for the two-dimensional SIFET. Therefore, whether the device proposed by Koo et al. realizes the SIFET is still under debate. It is noted that all the theoretical works mentioned above were performed without any scattering. However, scattering exists in reality and can be very important for spin diffusion [4, 13, 14].

In fact, a thorough understanding of spin diffusion in the two-dimensional SIFET with the scattering explicitly included can be obtained based on the kinetic spin Bloch equation (KSBE) approach [4], which has been successfully applied to study the spin diffusion/transport in various two-dimensional systems (e.g., GaAs quantum wells [13, 15–17] and Si/SiGe quantum wells [14]). In the framework of this approach, spins of electrons with wave vector \( \mathbf{k} \) precess in spatial domain with the frequency

\[
\omega_k = m^* (\Omega_k + g \mu_B B) / k_x
\]

during spin diffusion [13, 15]. Here, the spin-diffusion direction is set to be the \( \hat{x} \)-axis, \( m^* \) is the effective electron mass, \( \Omega_k \) is the D’yakonov–Perel’ (DP) [18] spin–orbit coupling term and \( B \) is the external magnetic field. In InAs quantum wells, the Rashba spin–orbit coupling [19] dominates and thus \( \Omega_k = 2\alpha (-k_x, k_y, 0) \) with \( \alpha \) being the Rashba coefficient modulated by the gate voltage. Moreover, the small external magnetic field used to magnetize the electrodes can be neglected when compared to the Rashba spin–orbit coupling [9]. Therefore, the spatial spin precession frequency

\[
\omega_k = 2\alpha \sin^2(-\tan \theta_k, 1, 0)
\]
the temperature ($T$) dependence of the spin-diffusion length should be mainly from the temperature dependence of the scattering in this case as the inhomogeneous broadening is insensitive on $T$ (i.e. $k_\parallel$ does not depend on the magnitude of $\mathbf{k}$).

In this paper, we numerically solve the KSBEs under the DP mechanism and obtain the gate-voltage dependence of the spin polarization at the detection point. Our result is in good agreement with the experiment of Koo et al at low and sufficiently high temperatures and hence is in favor of their claim of the realization of the SIFET.

We start our investigation from InAs quantum wells as presented in [9]. The nonlocal spin valve configuration is schematically shown in figure 1. The gate width $a$ of the square well are set to be 430 meV and 2 nm, respectively. The initial spatially uniform electron density $N_e = 2.5 \times 10^{12}$ cm$^{-2}$ and the effective electron mass $m^* = 0.05 m_0$ where $m_0$ is the free electron mass. The $\hat{x}$-axis polarized spins (the polarization $P_0$ is set to be 0.02) are injected at the left boundary $x = 0$ and diffuse along the $\hat{x}$-axis. The nonlocal voltage is detected at $x = x_0$, and the spin polarization at the right boundary $x = L$ is assumed to be 0. Due to the narrow well width, moderate electron density and small polarization, only the lowest sub-band is relevant in our investigation. The Rashba spin–orbit coupling coefficient $\alpha$ is taken from Koo et al [9], with the gate-voltage dependence shown in figure 2(a).

The KSBEs read

$$\frac{\partial \rho_k(x,t)}{\partial t} = -\frac{\partial \Psi(x,t)}{\partial x} \frac{\partial \rho_k(x,t)}{\partial k_x} - k_x \frac{\partial \rho_k(x,t)}{\partial k_x} - \frac{m^*}{2} \left[ \nabla \cdot \Omega_x \rho_k(x,t) \right] + \frac{\partial^2 \rho_k(x,t)}{\partial t^2} |_{\text{scat}} \quad (3)$$

Here, $\rho_k(x,t)$ are the single-particle density matrices of electrons with the in-plane wave vector $k$ at position $x$ and time $t$. $\Psi(x,t)$ is the electric potential satisfying the Poisson equation

$$\nabla^2 \Psi(x,t) = \epsilon [n(x,t) - N_0]/(\epsilon_0 \kappa_0 \epsilon_0) \quad (4)$$

with $n(x,t) = \sum \text{Tr}[\rho_k(x,t)]$ standing for the electron density at position $x$ and time $t$. $N_0$ the background positive charge density, $\epsilon_0$ the vacuum dielectric constant and $\kappa_0$ the relative static dielectric constant. $-i\Omega_x \cdot \sigma/2, \rho_k(x,t)$ is the coherent term describing the spin precession. $2\Delta (\partial^2 \rho_k(x,t))/\partial t^2 |_{\text{scat}}$ is the scattering term with the electron-impurity, electron-acoustic/longitudinal optical phonon, and electron–electron scatterings included. The details of the scattering term can be found in [4], [23] and [24]. It is noted that no fitting parameter is needed in our calculation.

To solve the KSBEs, the initial conditions are set as

$$\rho_k(0,0) = (F_{k_\parallel}^0 + F_{-k_\parallel}^0)/2 + (F_{k_\parallel}^0 - F_{-k_\parallel}^0)\sigma_z/2 \quad (5)$$

$$\rho_k(x > 0,0) = (F_{k_\parallel}^0 + F_{-k_\parallel}^0)/2 \quad (6)$$

and the boundary conditions are given as [13]

$$\rho_k(0,t) = [F_{k_\parallel}^0 + F_{-k_\parallel}^0 + (F_{k_\parallel}^0 - F_{-k_\parallel}^0)\sigma_z]/2 \quad (k_\parallel > 0) \quad (7)$$
\[ \rho_k(L, t) = \left( F_{k_1}^L + F_{k_1}^{-L} \right)/2 \quad (k_s < 0) \]  
\[ \Psi(0, t) = \Psi(L, t) = 0. \]

Here, \( x = L \) stands for the right boundary with \( L \) much longer than the spin-diffusion length. \( F_{k_1}^L \) (\( F_{k_1}^{-L} \)) stand for the Fermi distributions of electrons with spin parallel (antiparallel) to \( \hat{x} \)-axis determined by the temperature and the initial spin polarization at the left boundaries \( x = 0 \), and \( F_{k_1}^L \) (\( F_{k_1}^{-L} \)) are those determined by the corresponding conditions at the right boundary \( x = L \). It is noted that no external electric field along the spin-diffusion direction is applied and the electric potentials at the two boundaries are set as zero (equation (9)). The numerical scheme for solving the KSBEs can be found in detail in [13]. With the single-particle density matrices obtained by solving the KSBEs, the spin polarization at the point \( x \) at the steady state can be obtained as

\[ P(x, +\infty) = \sum_k \text{Tr}[\rho_k(x, +\infty)\sigma_z]/n(x, +\infty) \]
\[ = \sum_k P_k(x, +\infty). \]

Since the nonlocal voltage measured in the experiment is proportional to the spin polarization at the detection point [25, 26], we fit the experimental data measured at \( x_0 \) with \( P(x_0, +\infty) \).

In figure 2(b), we plot the gate-voltage \( V_G \) dependence of the spin polarization at the detection point \( x_0 = 1.25 \mu m \) by the solid curves and that of the experimentally measured nonlocal voltage by the dashed curves under different temperatures. It is noted that the Rashba spin–orbit coupling coefficient used in our calculation with the gate voltage from \(-5 \) to \(-3 \) V is obtained by linearly extending the \( \alpha-V_G \) curve presented by Koo et al [9]. From figure 2(b), one finds that our result is in good agreement with the experiment at 7 and 40 K. Moreover, more than one period of oscillation is found in our result, suggesting that Koo et al may also observe more periods if they enlarge the scope of measurement. When the temperature is higher, more impurities will be ionized and both the electron and impurity densities will increase [21]. This may explain the discrepancy between our theoretical result and the experimental data at \( T = 77 \) K. When \( T = 300 \) K and hence the scattering is strong, both our calculation and the experiment by Koo et al show that the oscillation of the spin polarization/nonlocal voltage disappears. In fact, due to the suppression on spin diffusion (mainly caused by the strengthened scattering, as revealed in the following), the spin-diffusion length becomes much shorter than the spacing between the injector and detector, and therefore no spin polarized signal can be observed at the detection point.

To further investigate the influence of scattering on spin diffusion, we first consider the much simplified case without the scattering and in-plane electric field; the single-particle density matrix for any \( k \) in the steady state can be obtained easily from the KSBEs as [13]

\[
\rho_k(x, +\infty) = \begin{cases} 
\exp(-i \omega_k \cdot \sigma \cdot x/2) \rho_k(0, 0) \exp(i \omega_k \cdot \sigma \cdot x/2), & k_s > 0 \\
\rho_k(L, 0), & k_s < 0
\end{cases}.
\]

where \( \omega_k \) is given in equation (2), indicating the spin precession frequency in the spatial domain. Then at the detection point,

\[ P_k(x_0, +\infty) = \left\{ \begin{array}{ll}
B_k [s^2 + (1 - s^2) \cos(\theta_\omega \sqrt{1 - s^2})], & k_s > 0 \\
0, & k_s < 0
\end{array} \right. \]

with \( s = k_y/k = \sin \theta_k \), \( \theta_\omega = 2m^*\alpha x_0 \) and \( B_k = (F_{k_1}^L - F_{k_1}^{-L})/N_e \). This solution with \( k_s > 0 \) has the same form as the result from Zainuddin et al (equation (5a) in [11]). Our result clearly indicates that the contribution to the total spin-polarized signal mainly comes from the \( k_s \)-positive states around the Fermi circle. Instead of summing \( P_k(x_0, +\infty) \) over the \( k_s \)-positive Fermi circle line as done by Zainuddin et al [11], we take into account all the \( k_s \)-positive states and obtain

\[ P(x_0, +\infty) \propto \int_{\theta_k}^{\pi} d\theta_k \left[ 1 - 2 \sin^2 \frac{m^* \alpha x_0}{\cos \theta_k} \cos^2 \theta_\omega \right]. \]

It is noted that the integration over \( \theta_k \) in equation (13) stands for the interference among different \( k \) states. However, one finds that this equation cannot fit the experimental data very well as the situation faced by Agnihotri and Bandyopadhyay [12] until the scattering is included as presented previously.

We then solve the KSBEs numerically by varying the impurity density artificially. Without losing generality, we take the temperature to be 7 K and the gate voltage to be 0. Under these conditions, the \( x \) dependence of the spin polarization with different impurity densities is plotted in figure 3. It is noted that the curve with \( N_i = 0 \) in this figure is obtained directly from equation (13). The impurity density dependence of the spin-diffusion length is plotted in the inset of figure 3. From this inset, one finds that the spin-diffusion length decreases sensitively with the increase in the impurity density. It is noted that even for the case of \( N_i = 0.5N_e \), the system is still in the weak scattering limit as \( \omega_L \tau_p = 1.19 > 1 \).
where $\omega_L = 2\alpha k_F$ is the spin precession frequency due to the spin–orbit coupling and $\tau_p$ is the momentum relaxation time. The decrease in the spin-diffusion length with the increase in the impurity density can be understood alternatively by means of the quasi-independent electron model [27–30], where the spin-diffusion length is characterized by $\sqrt{D_s \tau_s}$ with $\tau_s$ standing for the spin relaxation time and $D_s$ representing the spin-diffusion constant. $D_s$ decreases with the increasing scattering strength [4]. $\tau_s$ has the same tendency as $D_s$ as long as electrons are in the weak scattering limit [4]. Therefore, the spin-diffusion length decreases with the increase in scattering strength. This explains the disappearance of the oscillation of the spin-polarized signal at $T = 300$ K in figure 2(b) since the electron–phonon scattering is strengthened there.

In summary, we have investigated spin diffusion in $n$-type InAs quantum wells with the scattering explicitly included under the DP mechanism. The consistency between our theoretical result and the experimental data partially supports the claim by Koo et al [9] that a SIFET has been demonstrated. The essential role played by the scattering is also revealed. It is shown that the spin-diffusion length decreases with the increase in the impurity density in the weak scattering limit.

Acknowledgments

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