Voltage controlled spin precession in InAs quantum wells

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In this work we demonstrate that the device presented by Koo *et al.* [Science **325**, 1515 (2009)] in InAs quantum wells has indeed realized the Datta-Das spin-injected field effect transistor. The oscillation of the nonlocal voltage with the variation of the gate voltage at low temperature in the experiment can be well explained in the framework of the microscopic kinetic spin Bloch equation approach under the D'yakonov-Perel' mechanism with all the scattering explicitly included. We show that the scattering plays an important role in spin diffusion in such a system.

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In the past decades, a great deal of effort has been made for the realization of the spintronic devices.[1–5] The spin-injected field effect transistor (SIFET), proposed by Datta and Das in 1990,[6] is fundamental but posts some challenges to experiments (e.g., the spin-polarized injection and detection). Very recently Koo *et al.*[7] 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 the low temperature when the two ferromagnetic 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,[8] 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[7] makes little meaning and doubt is cast on the conclusion presented by Koo *et al.*. Later, Zainuddin *et al.*[9] 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 revealed by Agnihotri and Bandyopadhyay,[10] the experimental data actually do not match the equation for the two-dimension 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.

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,[5] which has been successfully applied to study the spin diffusion/transport in various two-dimensional systems (e.g., GaAs quantum wells[11–14] and Si/SiGe quantum wells[15]). In the framework of this approach, spins of electrons with the wave-vector $\mathbf{k}$ precess in spatial domain with frequency

$$\boldsymbol{\omega}_{\mathbf{k}} = m^*(\boldsymbol{\Omega}_{\mathbf{k}} + g\mu_B\mathbf{B})/(\hbar^2 k_x) \tag{1}$$

during the spin diffusion.[11,13] Here, the spin diffusion direction is set to be the $\hat{\mathbf{x}}$-axis, m^* is the effective electron mass, $\boldsymbol{\Omega}_{\mathbf{k}}$ is the D'yakonov-Perel' (DP)[16] spin-orbit coupling term and $\mathbf{B}$ is the external magnetic field. In InAs quantum wells, the Rashba spin-orbit coupling[17] dominates and thus $\boldsymbol{\Omega}_{\mathbf{k}} = 2\alpha(-k_y, k_x, 0)$ with α 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.[7] Therefore, the spatial spin precession frequency

$$\boldsymbol{\omega}_{\mathbf{k}} = 2\alpha m^*(-\tan\theta_{\mathbf{k}}, 1, 0)/\hbar^2 \tag{2}$$

depends on the polar angle $\theta_{\mathbf{k}}$ of the momentum. This $\mathbf{k}$ dependence of the precession frequency leads to the inhomogeneous broadening.[11,18] The inhomogeneous broadening itself causes reversible spin relaxation during spin diffusion.[5] One notices that the one-dimension model adopted by Koo *et al.*[7] actually excludes the inhomogeneous broadening by neglecting the transverse component of the momentum (i.e., k_y) and therefore is inappropriate. The scattering also plays an important role in spin diffusion which makes the relaxation irreversible and affects the spin diffusion length or even the precession frequency.[13,15] Furthermore, 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 ($\boldsymbol{\omega}_{\mathbf{k}}$ does not depend on the magnitude of $\mathbf{k}$). In this paper, we numerically solve the KSBEs under the DP mechanism. By including the influence of the scattering explicitly, we obtain the results in good agreement with the experimental data and hence demonstrate that the device presented by Koo *et al.* has realized the SIFET. Then, we further investigate the role played by the scattering in spin diffusion.

We start our investigation from InAs quantum wells as presented in Ref. 7. The depth V_0 and width a of the square well are set to be 390 meV and 2 nm, respectively. The initial spatially uniform electron density N_e is 2.7×10^{12} cm^{-2} and the effective electron mass $m^* = 0.05m_0$ where m_0 is the free electron mass. The $\hat{\mathbf{x}}$-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 $\hat{\mathbf{x}}$-axis. Due to the narrow well width, moderate electron density and small polarization, only the lowest subband is relevant in our investigation. The Rashba spin-orbit coupling coefficient α is taken from Koo *et al.*.[7] The impurity density N_i is estimated to be $0.11N_e$ according to the mobility reported by Koo *et al.*. The other parameters can be found in Ref. 19. The KSBEs read

$$\frac{\partial\rho_{\mathbf{k}}(x,t)}{\partial t} = -\frac{e}{\hbar}\frac{\Psi(x,t)}{\partial x}\frac{\partial\rho_{\mathbf{k}}(x,t)}{\partial k_x} - \frac{\hbar k_x}{m^*}\frac{\partial\rho_{\mathbf{k}}(x,t)}{\partial x} - \frac{i}{\hbar}[\mathbf{\Omega}_{\mathbf{k}}\cdot\frac{\boldsymbol{\sigma}}{2},\rho_{\mathbf{k}}(x,t)] + \frac{\partial\rho_{\mathbf{k}}(x,t)}{\partial t}\Big|_{\rm scat}. \quad (3)$$

Here, $\rho_{\mathbf{k}}(x,t)$ are the single-particle density matrices of electrons with the in-plane wave-vector $\mathbf{k}$ at position x and time t. $\Psi(x,t)$ is the electric potential satisfying the Poisson equation $\nabla_x^2\Psi(x,t) = e[n(x,t) - N_0]/(a\kappa_0\varepsilon_0)$ with $n(x,t) = \sum_{\mathbf{k}}\mathrm{Tr}[\rho_{\mathbf{k}}(x,t)]$ standing for the electron density at position x and time t, N_0 the background positive charge density, and κ_0 the relative static dielectric constant. $-\frac{i}{\hbar}[\mathbf{\Omega}_{\mathbf{k}}\cdot\boldsymbol{\sigma}/2,\rho_{\mathbf{k}}(x,t)]$ is the coherent term describing the spin precession. $\frac{\partial\rho_{\mathbf{k}}(x,t)}{\partial t}\big|_{\rm scat}$ is the scattering term with the electron-impurity, electron-phonon, and electron-electron scatterings included. The details of the scattering term can be found in Ref. 5.

To solve the KSBEs, the initial conditions are set as

$$\rho_{\mathbf{k}}(0,0) = (F^0_{\mathbf{k}\uparrow} + F^0_{\mathbf{k}\downarrow})/2 + (F^0_{\mathbf{k}\uparrow} - F^0_{\mathbf{k}\downarrow})\sigma_x/2, \quad (4)$$

$$\rho_{\mathbf{k}}(x>0,0) = (F^L_{\mathbf{k}\uparrow} + F^L_{\mathbf{k}\downarrow})/2, \quad (5)$$

and the boundary conditions are given as[13]

$$\rho_{\mathbf{k}}(0,t)|_{k_x>0} = (F^0_{\mathbf{k}\uparrow} + F^0_{\mathbf{k}\downarrow})/2 + (F^0_{\mathbf{k}\uparrow} - F^0_{\mathbf{k}\downarrow})\sigma_x/2, (6)$$

$$\rho_{\mathbf{k}}(L,t)|_{k_x<0} = (F^L_{\mathbf{k}\uparrow} + F^L_{\mathbf{k}\downarrow})/2, \quad (7)$$

$$\Psi(0,t) = \Psi(L,t) = 0. \quad (8)$$

Here, $x = L$ stands for the right boundary with L much longer than the spin diffusion length. $F^{0,L}_{\mathbf{k}\uparrow}$ ($F^{0,L}_{\mathbf{k}\downarrow}$) stand for the Fermi distributions of electrons with spin parallel (antiparallel) to the $\hat{\mathbf{x}}$-axis determined by the temperature and the initial polarization at the two boundaries. The numerical scheme for solving the KSBEs can be found in detail in Ref. 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

$$P(x,+\infty) = \sum_{\mathbf{k}}\mathrm{Tr}[\rho_{\mathbf{k}}(x,+\infty)\sigma_x]/n(x,+\infty) \equiv \sum_{\mathbf{k}} P_{\mathbf{k}}(x,+\infty). \quad (9)$$

Since the nonlocal voltage measured in the experiment is proportional to the spin polarization at the detection point,[20,21] we fit the experimental data measured at x_0 with $P(x_0,+\infty)$.

In Fig. 1, we plot the gate voltage dependence of the spin polarization at the detection point $x_0 = 1.25$ μm by the solid curves and that of the experimentally measured nonlocal voltage by the dashed curves under different temperatures. From the figure, one finds that our result is in good agreement with the experiment. It is noted that the good agreement with the experimental data is pretty attributed to the scattering.

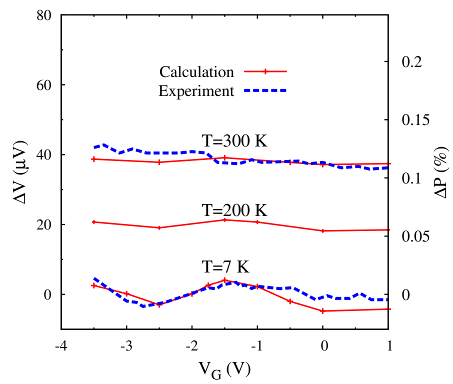

FIG. 1: (Color online) Gate voltage dependence of the spin polarization obtained from the KSBEs (solid curves with the scale on the right hand side of the frame) and that of the nonlocal voltage measured in the experiment[7] (dashed curves) at the detection point $x_0 = 1.25$ μm under different temperatures. The plots are shifted for clarity as Koo *et al.*.[7]

When we consider the much simplified case without the scattering and electric field, the single-particle density matrix for any $\mathbf{k}$ in the steady state can be obtained easily from the KSBEs as[13]

$$\rho_{\mathbf{k}}(x,+\infty) = \begin{cases} e^{\frac{-i\boldsymbol{\omega}_{\mathbf{k}}\cdot\boldsymbol{\sigma}}{2}x}\rho_{\mathbf{k}}(0,0)e^{\frac{i\boldsymbol{\omega}_{\mathbf{k}}\cdot\boldsymbol{\sigma}}{2}x}, & k_x > 0 \\ \rho_{\mathbf{k}}(L,0), & k_x < 0 \end{cases}, (10)$$

where $\boldsymbol{\omega}_{\mathbf{k}}$ is given in Eq. (2). Then at the detection point,

$$P_{\mathbf{k}}(x_0,+\infty) = \begin{cases} B_{\mathbf{k}}[s^2 + (1-s^2)\cos(\frac{\theta_{x_0}}{\sqrt{1-s^2}})], & k_x > 0 \\ 0, & k_x < 0 \end{cases} (11)$$

with $s = k_y/k = \sin\theta_{\mathbf{k}}$, $\theta_{x_0} = 2m^*\alpha x_0/\hbar^2$ and $B_{\mathbf{k}} = (F^0_{\mathbf{k}\uparrow} - F^0_{\mathbf{k}\downarrow})/N_e$. This solution with $k_x > 0$ has the same form as the result from Zainuddin *et al.* [Eq. (5a) in Ref. 9]. Our result clearly indicates that the contribution to the total spin-polarized signal mainly comes from the k_x-positive states around the Fermi circle. Instead of summing $P_{\mathbf{k}}(x_0,+\infty)$ over the k_x-positive Fermi circle line as done by Zainuddin *et al.*,[9] we take into account all the k_x-positive states and obtain

$$P(x_0,+\infty) \propto \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} d\theta_{\mathbf{k}}(1 - 2\sin^2\frac{m^*\alpha x_0}{\hbar^2\cos\theta_{\mathbf{k}}}\cos^2\theta_{\mathbf{k}}). (12)$$

It is noted that the integration over $\theta_{\mathbf{k}}$ in Eq. (12) stands for the interference among different $\mathbf{k}$ states. However, one finds that this equation still can not fit the experimental data as the situation faced by Agnihotri and Bandyopadhyay[10] until the scattering is included as presented previously.

We further investigate the influence of the scattering on spin diffusion by artificially varying the impurity density. 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 are plotted in Fig. 2.

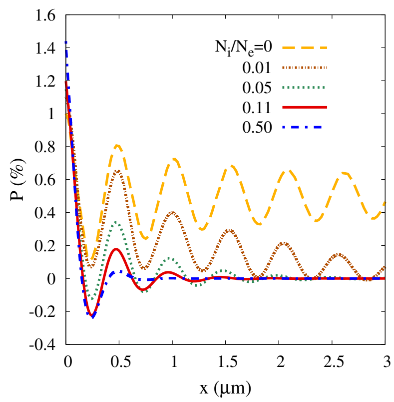

FIG. 2: (Color online) x dependence of P with different impurity densities. The case of $N_i = 0.11N_e$ corresponds to the experimental situation. The temperature is 7 K and the gate voltage is 0.

From the figure, 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 $\omega_L \tau_p = 3.6 > 1$, where $\omega_L = 2\alpha k_F/\hbar$ is the spin precession frequency due to the spin-orbit coupling and τ_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,[22–26] where the spin diffusion length is characterized by $\sqrt{D_s \tau_s}$ with τ_s standing for the spin relaxation time and D_s representing the spin diffusion constant. D_s decreases with the increasing scattering strength[5] and τ_s has the same tendency as D_s as long as electrons are in the weak scattering limit.[5] Therefore, the spin-diffusion length decreases with the increase in the impurity density.

In summary, we have investigated the spin diffusion in n-type InAs quantum wells under the DP mechanism. We show that the experiment performed by Koo *et al.*[7] has indeed realized the SIFET, in which the spin diffusion can be well understood in the framework of the KSBEs. 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.

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