Enhancement of spatial spin coherence in GaAs quantum wells

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Abstract. Spin transport of two-dimensional electron spin-transport in GaAs [001] quantum wells is investigated by Monte Carlo simulation. When the Rashba and the Dresselhaus effective magnetic field are comparable, spatial spin coherence is much enhanced for channels along [110] or [1-10] direction. This result clearly shows the possibility of “two-dimensional” spin-field-effect-transistors.

1. Introduction
For field-effect transistors (FETs), two-dimensional (2D) channels are desirable rather than narrow or quasi one-dimensional ones. Actually, FETs in integrated circuits have usually 2D channels. It is because narrow channels have some deficiencies, such as difficulties in fabrication and small current density. However, it is widely believed that narrow or quasi-one-dimensional channels are necessary for spin field-effect-transistors (spin-FETs), [1–3] to reduce strong D’yakonov-Perel’ (DP) spin relaxation. [4] Further, in the spin-FET proposed by Datta and Das [1], the electron transport must be ballistic. Recently, an operation method of spin-FETs robust for electron momentum-scatterings has been proposed, [5] but the necessity of point contacts is emphasized.

To realize 2D spin-FETs, spatial oscillation of spin polarization with sufficient coherence length is indispensable. In this study, we propose a method to enhance the spatial spin coherence of 2D electron gas and demonstrate its validity by Monte Carlo simulation.

2. Spin rotation in [001] quantum wells
Electron-spin rotation in semiconductors is due to the spin splitting of the conduction subband, comes from the atomic spin-orbit interaction and the lack of the spatial symmetry. The spin splitting is described by effective magnetic field \( \vec{B}_{\text{eff}}(\vec{k}) \) and electron spin \( \vec{S} \) precesses in accordance with

\[
\frac{d\vec{S}}{dt} = \vec{S} \times \gamma_0 \vec{B}_{\text{eff}}(\vec{k}),
\]

where \( \gamma_0 \) is the gyromagnetic ratio. In general, \( \vec{B}_{\text{eff}}(\vec{k}) \) depends on electron wave vector, and this \( \vec{k} \)-dependence causes temporal and spatial DP spin-relaxation. [4]
Figure 1. Total effective magnetic fields induced in an 8 nm GaAs [001] quantum well for $\alpha_{\text{SIA}} = \alpha_{\text{BIA}}$: (a) without and (b) with the $k^3$-term.

It is known that there are two types of effective magnetic field for quantum well structures: the Rashba [6] and the Dresselhaus [7] field. The Rashba field comes from the structure inversion asymmetry (SIA) or asymmetric potential due to external electric field $E_z$ applied perpendicular to the well. This effective magnetic field is given by [6, 8]

$$B_{\text{SIA}}(k_{||}) = \frac{1}{|\gamma_0|}\left[2\alpha_{\text{SIA}}(k_y, -k_x, 0)\right],$$

$$\alpha_{\text{SIA}} = \frac{\hbar^2}{2m^*E_g(3E_g + 2\Delta_{\text{SO}})} eE_z,$$

where $e$ is the elementary charge, $m^*$ the effective mass of electrons, $E_g$ the energy gap, and $\Delta_{\text{SO}}$ the spin-orbit splitting of the valence bands. Note that this field can be controlled externally through $E_z$. The Dresselhaus field comes from so called bulk inversion asymmetry (BIA) or asymmetry of the crystal lattice structure. Assuming strong confinement of electrons in a [001] quantum well with thickness $d$, we obtain

$$B_{\text{BIA}}(k_{||}) = \frac{1}{|\gamma_0|}\left[2\alpha_{\text{BIA}}(k_y, -k_x, 0) + \gamma_{\text{BIA}}(k_xk_y^2, -k_yk_x^2, 0)\right],$$

where

$$\alpha_{\text{BIA}} = \frac{\gamma_{\text{BIA}}}{2d},$$

$$\gamma_{\text{BIA}} = \frac{4\hbar^3}{3m_0m^*\sqrt{2m^*E_g}} \frac{1}{\sqrt{1 - \eta/3}},$$

$$\eta = \Delta_{\text{SO}}/(E_g + \Delta_{\text{SO}}),$$

and $m_0$ the electron rest mass. [7, 9] For small $k_{||} = (k_x, k_y)$, we can ignore the $k^3$-term of the left-hand side of Eq. (4). This field cannot be controlled externally.

The total effective magnetic field is given by the sum of these fields, or $B_{\text{tot}} = B_{\text{BIA}} + B_{\text{SIA}}$. Its $k_{||}$ dependence is not simple, except for $\alpha_{\text{SIA}} = \pm\alpha_{\text{BIA}} = \alpha$. [10, 11] For 8 nm GaAs quantum
Table 1. Parameters.

| Parameter                      | Value       |
|-------------------------------|-------------|
| material                      | GaAs        |
| well thickness \(d\)          | 8 nm        |
| temperature \(T\)             | 300 K       |
| electron sheet density \(N_0\)| \(0.5 \times 10^{12}\) cm\(^{-2}\) |
| in-plane electric field \(E_X\)| 1 kV/cm     |
| effective mass \(m^*\)        | 0.067 \(m_0\) |
| band gap \(E_g\)              | 1.424 eV    |
| spin-orbit splitting \(\Delta_{SO}\)| 0.346 eV |

well, electric field necessary for this condition, estimated by above equations, is 35 kV/cm or 3.5 mV/nm. We show in Fig. 1(a), the total magnetic field for \(\alpha_{SIA} = \alpha_{BIA}^D\) without the contribution of the \(k^3\)-term, or

\[
\vec{B}_{tot}(\vec{k}_||) \simeq \frac{2\alpha(k_y - k_x)}{|\gamma_0|} (1, 1, 0).
\]  

(8)

According to the symmetry of this field, we define [110], [100], and [001] as the \(X\), \(Y\), and \(Z\) directions, respectively. Then, we obtain

\[
\vec{B}_{tot}(\vec{k}_||) \simeq -\frac{2\sqrt{2}\alpha}{|\gamma_0|} k_X (1, 1, 0) = -\frac{4\alpha}{|\gamma_0|} k_X \vec{e}_Y,
\]

(9)

where \(k_X\) is the \(X\) component of \(\vec{k}_||\) and \(\vec{e}_Y\) is the unit vector along the \(Y\)-axis. Thus, the direction of this field is parallel to the \(Y\)-axis independent of \(\vec{k}_||\), and the field strength is proportional to \(k_X\).

Under this effective field, it is obvious that the spins parallel to the \(Y\) axis do not precess and are free from the DP spin relaxation. [5,12–14] On the contrary, when spins have \(XZ\) component, the precession frequency about the \(Y\)-axis depends on \(k_X\) as

\[
\omega(\vec{k}_||) = \frac{4\alpha}{\hbar} k_X.
\]

(10)

This dependence causes the temporal DP spin relaxation of 2D electron gas.

However, temporal spin relaxation is not related directly to the performance of spin-FETs, because the important is the spin orientation at the drain edge. For parabolic subbands, the electron velocity along the \(X\)-axis is given by \(v_X = \hbar k_X/m^*\), and the traveling time \(\Delta t\) for distance \(L_X\) along \(X\) is \(\Delta t = L_X/v_X = L_X m^*/(\hbar k_X)\). Thus the precession angle \(\theta\) during this travel is given by

\[
\theta = \omega(\vec{k}_||) \Delta t = \frac{4\alpha m^*}{\hbar^2} L_X.
\]

(11)

This indicates that the precession angle \(\theta\) depends only on \(L_X\) and is independent of \(L_Y\) and the traveling path of electrons. Therefore, the spatial spin-coherence length diverges. If we inject spin polarized electrons from an electrode along \(Y\) direction, the spin polarization shows the spatial oscillation along the \(X\)-axis.
Figure 2. Averages of spin components $<S_X>$, $<S_Y>$, and $<S_Z>$, and the absolute value $|<\vec{S}>|$ of normalized spin polarization for two-dimensional electrons in an 8 nm GaAs [001] quantum well for $\alpha_{BIA}^{2D} \approx \alpha_{SIA} = 10.00$ meV/Å as a function of the traveling distance along $X$: (a) without and (b) with the $k^3$-term.

3. Numerical Results

In Fig. 2, we show the results of Monte Carlo simulation for electron transport with spin precession. [15] We have taken into account the momentum scatterings by optical and acoustic phonons and impurities. Electron transport along $Y$-direction as well as that along $X$ is considered. The important parameters used in the simulation are shown in Table 1. Fig. 2(a) shows the result for the effective magnetic field of Fig. 1(a). The spin polarization, initially along the $X$-axis, shows clear oscillation without spatial relaxation. However, the $k^3$-term is expected to reduce spatial spin coherence, in reality. Figure 1(b) shows the total field with the contribution of the $k^3$-term. Though the field is modified considerably for larger $k_\parallel$, the effect is not so strong for the Fermi wave vector for the present electron sheet-density $0.5 \times 10^{12}$ cm$^{-2}$, shown by the circle in the figure. The result of the simulation with the $k^3$-term is shown in Fig. 2(b). The coherence length is limited, but is about 10 $\mu$m, which is sufficient for device application.

In actual spin FETs, however, the channel length is fixed, and $\alpha_{SIA}$ is controlled through the gate bias. Therefore, it is rather meaningless to investigate only the condition of $\alpha_{SIA} = \alpha_{BIA}^{2D}$. In Fig. 3, we show the spin polarization as a function of $\alpha_{SIA}$ for channel length $L_X = 1.5 \mu$m, where $<S_X> \sim 0$ for $\alpha_{SIA} = \alpha_{BIA}^{2D}$, for example. For positive $\alpha_{SIA}$, the amplitude of $<S_X>$ is sufficiently large and that of $<S_Z>$ is also considerable. For negative $\alpha_{SIA}$, $<S_X>$ does not oscillate but has maximum at $\alpha_{SIA} \sim -\alpha_{BIA}^{2D}$, where electron spins polarized along the $X$-axis do not precess.

4. Two-dimensional spin-FETs

The above results clearly show that 2D spin-FETs are possible. We can control the rotation of the spin polarization accompanied by 2D electric current along [1 1 0] or equivalent directions. Changing the gate bias, we can control the Rashba field and the spin polarization at the drain edge of 2D channel. Though the gate bias also affects the electron sheet density in actual devices, the spin precession depends only on the applied electric field and is independent of the electron
density.

If we want not to change the electron density, we can use the back gate. [16, 17] In this case, it is easy to change the sign of the gate electric field and that of $\alpha_{SIA}$, and we can use the conditions of $\alpha_{SIA} = \alpha_{2D}^{BIA}$ and $\alpha_{SIA} = -\alpha_{2D}^{BIA}$ as “on” and “off” states.

5. Summary
In this study, we have demonstrated that the rotation of spin polarization with sufficient coherence length is possible for 2D electron transport in quantum wells. The method is simple and applicable to 2D spin-FETs.

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