D’yakonov-Perel’ spin relaxation under electron-electron collisions in \( n \)-type QWs

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The D’yakonov-Perel’ spin relaxation mechanism in \( n \)-doped GaAs/AlGaAs quantum wells (QWs) has been studied both theoretically and experimentally. The temperature dependence of the spin relaxation time has been calculated for arbitrary degeneracy of the 2D electron gas. The comparison between theory and experiment shows that, in high-mobility \( n \)-doped QWs, the studied spin decoherence is controlled by electron-electron collisions.

At present it is widely accepted that in zinc-blende-lattice \( n \)-doped quantum well structures the spin-relaxation of conduction electrons is dominated by the D’yakonov-Perel’ (DP) mechanism. In this mechanism the spin splitting of electronic states acts as an effective magnetic field with the Larmor frequency \( \Omega_k \) dependent on the value and direction of the electron wave vector \( k \). The related spin relaxation time is given by

\[
\frac{1}{\tau_s} \propto \langle \Omega^2 \rangle,
\]

where \( \tau \) is the microscopic relaxation time controlling spin decoherence. Recently we have shown that the inverse time \( \tau^{-1} \) has contributions not only from electron momentum scattering processes responsible for the conductivity but also by electron-electron collisions which do not affect the electron mobility. Experimentally, the effect of electron-electron collisions on the spin dynamics has been recently demonstrated by Brand et al. In Ref. only the case of a nondegenerate 2D electron gas is treated quantitatively while the data are obtained on a degenerate high-mobility gas. The purpose of this work is to extend the theory to arbitrary electron degeneracy and compare the temperature dependence of \( \tau_s \) with the experiment.

A convenient form to represent temperature dependence of the spin relaxation time is to write \( \tau_s \) as

\[
\tau_s^{-1} = \Omega_0^2 \tau^*,
\]

where \( \Omega_0 \) is the effective Larmor frequency at the Fermi energy at zero temperature and \( \tau^* \) is a temperature-dependent parameter which can be compared with the momentum relaxation time \( \tau_p \) obtained from measurement of the Hall mobility. The representation is usefully applied in the scattering-dominated regime, where \( \Omega_0 \ll \tau^{-1} \), realized at \( T \sim 10 \) K and higher. At the low temperature \( T = 1.8 \) K, the electron spin polarization evolves as heavily damped oscillations of frequency \( \Omega_0 \approx 0.19 \) ps\(^{-1} \) and \( \tau^* \) is found from the exponential decay of these oscillations. Thus, instead of \( \tau_s \), we present in Fig. 1 the temperature dependence of the above defined time \( \tau^* \).

Values of \( \tau^* \) extracted from the experiment are plotted in Fig.1 by crosses together with the momentum relaxation time \( \tau_p \) (full circles). The spin polarization was monitored by time-resolved optical response of a sample in which the 2D gas was confined in a (001)-oriented 10-nm \( n \)-doped GaAs/AlGaAs quantum well structure. Electron concentration was estimated to be \( N_s = 1.86 \times 10^{11} \) cm\(^{-2} \) and Hall measurements showed \( N_s \) to be approximately constant at \( T \) below 100 K. The transport relaxation time \( \tau_p \) was extracted from the Hall mobility.

The inverse electron spin relaxation time in the symmetric GaAs QW is given by

\[
\frac{1}{\tau_{zz}} = \langle \Omega_{1k}^2 + \Omega_{3k}^2 \rangle \tau_p,
\]

where \( h\Omega_{1k} = 2\beta k((\langle k_z^2 \rangle - k^2)/4) \), \( h\Omega_{3k} = \beta k^3/2 \), \( \beta \) is the constant describing spin-orbit splitting of the conduction band in bulk GaAs and \( \langle k_z^2 \rangle \) is the quantum mechanical average of the squared electron wave vector along the growth axis. In Eq. electron-electron collisions are neglected. The dotted line in Fig. 1 presents \( \tau^* \) calculated from with \( \tau_p \) given by the full circles. Definitely, this line does not fit experimental points (crosses) and, therefore, one can conclude that the account for momentum scattering processes only is not sufficient to explain the experimental results. The next step is to include electron-electron collisions into consideration and calculate the times \( \tau_s \) and \( \tau^* \) with allowance for both electron-electron and momentum scattering.

In the frame of kinetic theory, the electron distribution in the wave vector and spin spaces is described by a \( 2 \times 2 \) spin-density matrix \( \rho_k = f_k + s_k \cdot \vec{\sigma} \), where \( \sigma_\alpha \) are the Pauli matrices. Here \( f_k = \text{Tr}(\rho_k/2) \) is the distribution function of electrons in the \( k \)-space, and \( s_k = \text{Tr}[\rho_k(\vec{\sigma}/2)] \) is the average spin in the \( k \) state. If we neglect the spin splitting then, for arbitrary degeneracy of an electron gas with non-equilibrium spin-state occupation but equilibrium energy distribution within each spin branch, the electron spin-density matrix is the Fermi-Dirac distribution function with different chemical potentials for the spin \( \pm 1/2 \). If the spin splitting is non-zero but small as compared to \( \hbar/\tau^* \), the
distribution function $\text{Tr}[\rho_k/2]$ does not change, whereas the spin vector acquires a correction $\delta s_k$ proportional to the spin splitting.

The quantum kinetic equation for the spin pseudovector taking into account both electron-electron collisions and elastic (or quasi-elastic) momentum scattering has the form

$$
\frac{\partial s_k}{\partial t} + \Omega_k \times s_k + \frac{\delta s_k}{\tau_p} + Q_k\{s, f\} = 0 ,
$$

where $Q_k\{s, f\}$ is the electron-electron collision integral and $\tau_p$ is the momentum scattering time. In the particular case of low spin polarization the electron-electron scattering rate has the form

$$
Q_k\{s, f\} = \frac{2\pi}{\hbar} \sum_{k', p, p'} \delta_{k+k', p+p'} \delta(E_k + E_{k'} - E_p - E_{p'})
$$

$$
\times \left\{ 2V_{k-p}^2 M(k, k', p, p') - V_{k-p} V_{k-p'} [M(k, k', p, p') + M(k', k, p, p')] \right\} .
$$
Here $V_q$ is the Fourier transform of the electron-electron interaction potential,

$$M(k, k', p, p') = s_k F(k'; p, p') - s_p F(p'; k, k'),$$

$F(k_1, k_2, k_3) = f_{k_1}(1 - f_{k_2} - f_{k_3}) + f_{k_2} f_{k_3}$ and $f_k$ is the equilibrium Fermi-Dirac distribution function. The term proportional to $2V^2_k - p$ is due to the direct Coulomb interaction whereas the term proportional to $V_k p V_{k'}$ comes from the exchange interaction.

The spin-relaxation time governed by electron-electron collisions was calculated allowing only for the linear-$k$ term in $\Omega_k$ and using a fixed value of $\tau_p$. We used statically screened 2D Coulomb potential for $V_q$. The solid line in Fig. 1 shows temperature dependence of $\tau^* = \tau^{-1}_s \Omega_0^{-2}$ calculated taking into account electron-electron collisions only ($\tau_p = \infty$). A non-monotonous behavior of this time can be understood as follows. In the limit of low temperatures, for the degenerate two-dimensional electron gas, $\langle \Omega^2_k \rangle$ tends to a constant value $\Omega_0^2$ while the electron-electron scattering rate $\tau^{-1}_{ee}$ vanishes as $T^2 \ln T$. Therefore, if momentum scattering is neglected the scattering time $\tau^* \rightarrow \infty$. The allowance for electron momentum scattering stabilizes both $\tau^{-1}_s$ and $\tau^*$ at $T = 0$. With rising temperature the role of electron-electron collisions increases resulting in a decrease of $\tau^*$. In the opposite limit of high temperatures the electron gas becomes nondegenerate in which case $\tau_{ee} \propto T$, $\langle \Omega^2_k \rangle \propto T$ and the spin relaxation rate due to electron-electron collisions increases with temperature according the $T^2$ law. The dependence $\tau^*(T)$ exhibits a minimum near the transition from degenerate to nondegenerate statistics when the chemical potential of electron gas reaches the conduction band bottom.

Some discrepancy between the theoretical curve (dashed) and experimental points (crosses) can probably be eliminated by taking into account that, in the 10-nm GaAs/AlGaAs QW, the electron wave function has a quasi-2D character owing to its spread within the well and electron tunnelling into the barriers.

In conclusion, we have shown both experimentally and theoretically that the D’yakonov-Perel’ spin relaxation may be controlled by electron-electron collisions which do not affect the mobility in the same way as by any other carrier scattering process.

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