Effect of Singwi-Tosi-Land-Sjölander local field correction on spin relaxation in \textit{n}-type GaAs quantum wells at low temperature

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We study the effect of the Singwi-Tosi-Land-Sjölander local field correction on spin relaxation/dephasing in \textit{n}-type GaAs quantum wells at low temperature by constructing and numerically solving the kinetic spin Bloch equations. We calculate the local field factor \( G(q) \) in quantum wells by numerically solving three equations which link the local field factor, the structure factor, and the dielectric function, self-consistently. Such a correction reduces both the electron-electron Coulomb scattering and the Coulomb Hartree-Fock term. We compare the spin relaxation times with and without this correction under different conditions such as temperature, electron density, well width and spin polarization. We find that this correction leads to a decrease/increase of the spin relaxation time in the strong/weak scattering limit. At high spin polarization, it reduces the Hartree-Fock term and consequently tends to decrease the spin relaxation time. The modification of the spin relaxation time by the local field correction is more or less moderate either due to the coexistence of scattering other than the Coulomb scattering at low spin polarization and/or due to the competing effects from the Coulomb scattering and the Coulomb Hartree-Fock term at high polarization.

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The study of spin relaxation/dephasing (R/D) in semiconductors is of great interest to the spintronic society recently. It is well known that the D’yakonov-Perel’ (DP) mechanism\(^{9,10,11,12,13,14,17}\) is the dominant spin R/D mechanism in both bulk and two-dimensional \textit{n}-type zincblende semiconductors\(^6\). This mechanism is due to the momentum-dependent spin state splitting, which originates from the Dresselhaus spin-orbit coupling\(^6\) in crystals without inverse symmetry and the Rashba spin-orbit coupling\(^6\) in quantum wells (QWs) with asymmetric potential. For (001) GaAs QW with small well width, the Dresselhaus term can be written as:

\[
\Omega_{k_x} = \frac{\gamma k_x (k_y^2 - k_z^2)}{2}, \quad \Omega_{k_y} = \frac{\gamma k_y (k_z^2 - k_x^2)}{2}, \quad \Omega_{k_z} = \frac{\gamma k_z}{2},
\]

in which \( (k_x^2) \) represents the average of the operator \(-(\partial/\partial z)^2\) over the electronic state of the lowest subband\(^6\).

It was first pointed out by Wu et al. from a fully microscopic approach that any type of scattering, including the spin conserving electron-electron Coulomb scattering, can lead to irreversible spin R/D in the presence of inhomogeneous broadening. Similar claim was also made later by Glazov and Ivchenko. This has been verified experimentally by Leyland et al. Moreover, Weng and Wu also predicted an interesting effect that the spin R/D can be suppressed by increasing the initial spin polarization due to the effective magnetic field which originates from the Hartree-Fock (HF) contribution of the Coulomb interaction\(^11\). This prediction has also been confirmed experimentally very recently. However, in all the previous works\(^2,10,11,12,13,14,17\) the electron-electron Coulomb interaction is treated under the random phase approximation (RPA). Usually, the RPA is considered to be good only at small \( r_s \) with \( r_s = (\sqrt{\pi n a_0})^{-1} \) representing the dimensionless coupling parameter for the two-dimensional electron gas with electron density \( n \) and effective Bohr radius \( a_0 \). Such kind of approximation does not involve the correction which describes the electron charge depletion nearby the electron, known as the exchange-correlation hole. This correction beyond the RPA is so-called the local field correction (LFC). It must be taken into account for properties when the electron-electron interactions plays an important role, \textit{e.g.}, the spin Coulomb drag effect. This LFC can be introduced through a momentum-dependent correction factor \( G(q) \) in the dielectric function\(^{20,21,22,23,24,25,26,27}\) by using the equation of motion method:

\[
G_{\text{STLS}}(q) = \frac{1}{n} \int \frac{dq'}{(2\pi)^3} \frac{\mathbf{q} \cdot \mathbf{q'} - [S(q - q') - 1]}{q'^2}.
\]

They suggested that one can solve a trial of equations which link the three quantities: \( G_{\text{STLS}}(q) \), the structure factor \( S(q) \) and \( \varepsilon(q, \omega) \) self-consistently. Later on, there
are many other efforts on calculating this factor in three-dimensional (3D) systems. In ideal two-dimensional (2D) electron gas/liquid, the local field factors $G_{2D}(q)$ were also calculated similar to the 3D case mentioned above.

In this paper, we calculate $G^w(q)$ in n-type GaAs QWs by solving three equations which link the three functions $G^{w}(q)$, $S^{w}(q)$, and $\varepsilon^{w}(q,\omega)$ self-consistently. These equations are a little different from those in the bulk system and ideal 2D system can be written as:

\begin{equation}
\varepsilon^{w}(q,\omega) = 1 - \frac{\bar{v}_q \bar{P}^{(1)}(q,\omega)}{1 + \bar{v}_q G^w(q) P^{(1)}(q,\omega)},
\end{equation}

\begin{equation}
G^w(q) = -\frac{1}{n} \int \frac{d\mathbf{q}' \cdot \mathbf{q}}{(2\pi)^2 q'^2 v_q} \left[ S^w(q - q') - 1 \right],
\end{equation}

\begin{equation}
S^w(q) = -\frac{1}{n\bar{v}_q} \int_0^{\infty} \frac{d\omega}{\pi} \text{Im}\left[ \varepsilon^w(q,\omega) \right],
\end{equation}

where $\bar{v}_q = \sum_q v_q |I(q_z)|^2$ and $v_Q = 4\pi q^2/Q^2$ with $Q \equiv (q, q_z)$ are the screened quasi-2D and bare bulk Coulomb potential respectively. $|I(q_z)|^2$ denotes the form factor of square QWs with finite well depth, whose expression can be found in Ref. 31.

We plot the wave-vector dependence of $G^{w}(q)$ in GaAs/Al$_0.4$Ga$_{0.6}$As QWs with well width $a = 10$ nm under different conditions in Fig. 4. In Fig. 4(a), $G^{w}(q)$ are plotted at different temperatures ($T$) when the electron density $n = 2.5n_0 = 2.5 \times 10^{11}$ cm$^{-2}$ (the corresponding $r_s = 1.09$). One can see that $G^{w}(q)$ increases very quickly with temperature. The electron-density dependence of $G^{w}(q)$ is plotted in Fig. 4(b) at $T = 30$ K, where the largest electron density is chosen to be $5n_0$ ($r_s = 0.77$), still beyond the RPA limit. It is seen that $G^{w}(q)$ decreases with electron density $n$. We further present $G^{w}(q)$ at different spin polarizations $P$ when $n = 2.5n_0$ and $T = 30$ K. One finds that $G^{w}(q)$ increases slightly with $P$. When we use the infinite-well-depth assumption and let the well width to be very small, our $G^{w}(q)$ tends to $G_{2D}(q)$. Facilitated with the local field factor, we turn to investigate the effect of LFC on spin dephasing in n-type (001) GaAs/Al$_0.4$Ga$_{0.6}$As QWs. We construct the kinetic spin Bloch equations by using the nonequilibrium Green function method:

\begin{equation}
\dot{\rho}_{k,\sigma\sigma'} = \dot{\rho}_{k,\sigma\sigma'}^{\text{coh}} + \dot{\rho}_{k,\sigma\sigma'}^{\text{scatt}},
\end{equation}

where $\rho_{k,\sigma\sigma'}$ denote the single particle density matrix elements with the diagonal and off-diagonal elements to be the electron distribution functions $f_{k\sigma}$ and spin coherence $\rho_{k,\sigma\sigma'}$. The coherent terms $\dot{\rho}_{k,\sigma\sigma'}^{\text{coh}}$ describe the precession of the electron spin due to the effective magnetic field $\mathbf{Q}(k)$ [Eqs. (13)] as well as the HF Coulomb interaction. In the scattering term $\dot{\rho}_{k,\sigma\sigma'}^{\text{scatt}}$, the electron-LO-phonon, the electron-AC-phonon, the electron-nonmagnetic impurity and the electron-electron Coulomb scattering are included explicitly. Their expressions can be found in Refs. [32,12]. After numerically solving the kinetic spin Bloch equations, one can obtain the spin dephasing and relaxation times from the temporal evolutions of the spin coherence $\rho_{k,\sigma\sigma'}$ and the electron distribution function $f_{k,\sigma}$. In Fig. 2, we present the temperature dependence of the spin relaxation time (SRT) in QW with $(\tau_{LFC})$ and without $(\tau)$ the LFC for two different electron densities $n = 2.5n_0$ and $5n_0$. The spin polarization is small ($P = 2\%$) in the calculation. The well width $a = 10$ nm. We choose the impurity density to be $0.0084n_0$, corresponding to that we used in Ref. 17. In our calculation,
SR T decreases with the total scattering strength $1/\tau_p^*$ with $\tau_p^*$ representing the momentum relaxation time in the weak scattering limit ($|\Omega|\tau_p^* > 1$), but increases with the total scattering strength in the strong scattering limit ($|\Omega|\tau_p^* \ll 1$). Therefore, at very low temperature, the system is in the weak scattering limit and the decrease of the Coulomb scattering leads to $\tau_{\text{LFC}} > \tau$. At higher temperature, however, the system is in the strong scattering limit. Consequently, with the decrease of the Coulomb scattering, $\tau_{\text{LFC}} < \tau$. It should be noted that the amplitude of the modification of the SRT is no more than one order of magnitude because of the existence of other scattering terms such as the electron-phonon and the electron-impurity scattering.

From Fig. 2 one also finds that the reduction of the SRT by the LFC for the case with $n = 2.5n_0$ is much larger than that with $n = 5n_0$. Therefore, it is necessary to further investigate the density dependence of the SRT with/without the LFC. In Fig. 3 the SRTs are plotted against the electron density $n$ for different well widths $a = 10 \text{ nm}$ and $20 \text{ nm}$ when $T = 30 \text{ K}$ and $P = 2 \%$. In order to make the figure clear, we re-scale the SRTs for the case with $a = 20 \text{ nm}$ by multiplying 0.2. As the system is in the strong scattering limit, $\tau_{\text{LFC}} < \tau$. Moreover, the larger the electron density is, the smaller the difference between $\tau_{\text{LFC}}$ and $\tau$ becomes. This is because the reduction of the Coulomb scattering due to the LFC becomes weaker for larger electron density. This can be seen from Fig. 1b that $G(q)$ decreases with $n$, especially at large $q$ near the Fermi momentum $k_F$.

Finally, we investigate the spin polarization dependence of $\tau$ and $\tau_{\text{LFC}}$ for different temperatures and electron densities as shown in Fig. 4. In the calculation, the well width $a = 20 \text{ nm}$. It is interesting to see that there is a crossover at certain spin polarization. $\tau_{\text{LFC}} < \tau$ for small spin polarization and $\tau_{\text{LFC}} > \tau$ for large spin polarization. These features origin from the dual effects of the Coulomb interaction at high spin polarization. The first effect has been said above. The second one is from the effective magnetic field in the HF term which suppresses the spin R/D at high spin polarization. This effect has been observed in experiments very recently. As the LFC always reduces the Coulomb interaction, the LFC can lead to a decrease of the SRT by reducing the HF term at high spin polarization. It is seen from the figure that for small spin polarization, as the contribution from the HF term is negligible and the system is in the strong scattering limit, inclusion of the LFC always results in a decrease of the SRT. However, when the polarization becomes large enough, the contribution from the HF term becomes important and the system turns into the weak scattering limit.
scattering limit as the HF term enhances the amplitude of effective magnetic field $\Omega$ along the $z$-axis. In this regime, inclusion of the LFC results in a competing effect from the HF term and the scattering term. Our results indicate that when the polarization is large enough, the effect from the scattering is stronger and consequently the SRT is increased with the inclusion of the LFC.

In conclusion, we study the STLS LFC on the spin relaxation/dephasing in $n$-type GaAs (001) QWs at low temperature by constructing and numerically solving the kinetic spin Bloch equations. The LFC takes into account the screening from the additional exchange-correlation hole ignored in the RPA. The LFC reduces both the Coulomb scattering and the Coulomb HF interaction. It is known that the decrease of the Coulomb scattering can lead to a decrease (an increase) of the SRT in the strong (weak) scattering limit whereas the decrease of the Coulomb HF interaction results in a decrease of the SRT at high spin polarization. After comparing the SRT with and without the LFC under different conditions, we find that the LFC can lead to a decrease of the SRT in the strong scattering limit for small spin polarization. It also leads to a decrease of the SRT while the spin polarization getting larger, and finally leads to an increase when the spin polarization is large enough.

It is noted that in our recent theoretical comparison with the experiment, the LFC was ignored. From this investigation, we conclude that this approximation is acceptable. This is because when the electron density is about 2.1$n_0$, the difference between $\tau_{\text{LFC}}$ and $\tau$ is very small according to Fig. 3.

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