Spin dynamics in semiconductor nanostructures

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We review our theoretical investigation on the spin relaxation/dephasing in spin precession and spin diffusion/transport in semiconductor nanostructures based on the kinetic spin Bloch equation approach.

I. INTRODUCTION

Much attention has been devoted to the electron spin dynamics in semiconductors for the past three decades.1,2 Especially, recent experiments have shown extremely long spin lifetime (up to hundreds of nanoseconds) in -type bulk Zinc-blende semiconductors (such as GaAs).3,4,5 Moreover, a lot more investigations have been performed on various low dimensional systems.6 The spin diffusion/transport has also been studied experimentally and very long spin injection length are reported.7 These findings show the great potential for using the spin degree of freedom in place of, or in addition to, the charge degree of freedom for device application such as qubits and spin transistors. A thorough understanding of the spin relaxation/dephasing (R/D) in the spin precession and spin diffusion/transport is essential for such application.

It is understood that the D’ayakonov-Perel’ (DP) mechanism is the leading spin R/D mechanism in n-type Zinc-blende semiconductors.8 Many theoretical works have been carried out to study the spin relaxation in various systems,9 based on the single-particle formula

\[
\frac{1}{\tau} = \frac{1}{2} \int_0^\infty dE_k \frac{E_k (f_{k1/2} - f_{k-1/2}) \tau_p(k) \langle \mathbf{h}^2(k) \rangle}{(f_{k1/2} - f_{k-1/2})^2} .
\]

(1)

Here \(\tau_p(k)\) is the momentum relaxation time which is due to the electron-phonon and electron-impurity scattering. \(f_{k\sigma}\) stand for the electron distribution functions of spin \(\sigma\). \(\mathbf{h}(k)\) is the DP term which serves as an effective magnetic field and is composed of the Dresselhaus term10 due to the bulk inversion asymmetry (BIA) and the Rashba term11 due to the structure inversion asymmetry (SIA). \(\langle \mathbf{h}^2(k) \rangle\) denotes the average of \(\mathbf{h}^2(k)\) over all directions of \(\mathbf{k}\). In GaAs quantum well (QW), the Dresselhaus term is the leading term and \(\mathbf{h}\) has the form:

\[
\begin{align*}
\mathbf{h}_x(k) &= \gamma_1 k_y (k_y^2 - \langle k_y^2 \rangle) , \\
\mathbf{h}_y(k) &= \gamma_2 k_y (k_y^2 - \langle k_y^2 \rangle) , \\
\mathbf{h}_z(k) &= 0 ,
\end{align*}
\]

(2)

It was shown recently by Wu et al. from a full microscopic kinetic-spin-Bloch-equation (KSBE) approach that the single-particle approach is inadequate in accounting for the spin R/D both in the time domain14,15,16,17,18 and in the space domain.19,20,21,22 The momentum dependence of the effective magnetic field (the DP term) and the momentum dependence of the spin diffusion rate along the spacial gradient19 or even the random spin-orbit coupling (SOC)23 all serve as inhomogeneous broadenings.15,16 It was pointed out that in the presence of inhomogeneous broadening, any scattering, including the carrier-carrier Coulomb scattering, can cause an irreversible spin R/D.15,16 Moreover, besides the spin R/D channel the scattering provides, it also gives rise to the counter effect to the inhomogeneous broadening. The scattering tends to drive carriers to a more homogeneous state and therefore suppresses the inhomogeneous broadening. Finally, this approach is valid in both strong and weak scattering limits and can be used to study systems far away from the equilibrium.

In this paper, we review the KSBE approach in various nanostructures and under different conditions. The paper is organized as follows: In Sec. 2 we set up the KSBEs. In Sec. 3 we review the results of the spin R/D in the time domain. The results of the spin R/D in the spin transport/diffusion are reviewed in Sec. 4. We conclude in Sec. 5.

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II. MODEL AND KSBES

We start our investigation from an n-type zinc-blende semiconductor QW with the growth direction along the z-axis. The well width is assumed to be small enough so that only the lowest subband is relevant. Sometimes a moderate magnetic field B is applied along the x-axis (in the Voigt configuration).

By using the nonequilibrium Green function method with gradient expression as well as the generalized Kadanoff-Baym Ansatz,24 we construct the KSBEs as follows:

\[ \dot{\rho}_k(r, t) = \dot{\rho}_k(r, t)|_{\text{diff}} + \dot{\rho}_k(r, t)|_{\text{coh}} + \dot{\rho}_k(r, t)|_{\text{scat}}. \]

Here \( \rho_k(r, t) \) is the density matrix of electrons with momentum \( k \) at position \( r = (x, y) \) and time \( t \). The off-diagonal elements \( \rho_{k\uparrow\downarrow} = \rho_{k\downarrow\uparrow}^\ast \) represent the correlations between the spin-up and down states. \( \dot{\rho}_k(r, t)|_{\text{diff}} = \{\nabla r \cdot \nabla k \rho_k(r, t)\}/2 \) are the driving terms from the external electric field. Here \( \nabla k \rho_k(r, t) = k^2/2m^* + [g \mu B + h(k)] \cdot \sigma/2 - e\Psi(r) + \nabla_\text{eff}(r, t) \) with \( \nabla_\text{eff}(r, t) = -\sum_q V_q \rho_k - q(r, t) \) representing the Hartree-Fock (HF) term. \( m^* \) is the effective mass. \( \Psi(r) \) is determined from the Poisson equation. The bracket \( \{A, B\} = AB - BA \) is the anti-commutator. \( \dot{\rho}_k(r, t)|_{\text{coh}} = \dot{i}[g \mu B + h(k)] \cdot \sigma/2 + \nabla_\text{eff}, \rho_k \).

The scattering terms are different depending on different statistics.25 One is the collinear statistics where the equilibrium state is taken as the Fermi distribution of states. 25

\[ \rho_k(r, t) = \rho_{k\uparrow\downarrow}|_{\text{coh}} + \rho_{k\uparrow\downarrow}|_{\text{scat}}. \]

Here \( \rho_k(r, t) = \rho_{k\uparrow\downarrow}|_{\text{coh}} + \rho_{k\uparrow\downarrow}|_{\text{scat}} \) are the density matrices of the KSBEs with all the scattering explicitly included. The spin relaxation time \( T_1 \) is determined from the slope of the envelope of \( \Delta N = \sum_k (f_{k\uparrow} - f_{k\downarrow}) \). The irreversible spin dephasing time \( T_2 \) is associated with the incoherently summed spin coherence \( \rho = \sum_k |\rho_{k\uparrow\downarrow}(t)| \) whereas the ensemble spin dephasing time \( T_2 \) is defined from the slope of the envelope of the coherently summed spin coherence \( \rho' = |\sum_k \rho_{k\uparrow\downarrow}(t)| \). Similarly for spin diffusion/transport, the spin diffusion length can be determined from the spacial evolution of \( \Delta N \) in the steady state.19

III. SPIN R/D

In this section we review our results of spin R/D in semiconductor nanostructures based on SKBE approach. It was shown that any spin conserving scattering, including the electron-electron Coulomb scattering, can cause an irreversible spin R/D in the presence of the inhomogeneous broadening.16,17,18 The energy dependence of the g factor15 and the momentum dependence of the DP term16,17,18 all serve as the inhomogeneous broadening. In quantum wire, the inhomogeneous broadening can be quantified by the standard deviation of the Larmor frequencies which well corresponds to the resulting spin dephasing time.26 It is further shown in GaAs (110) QWs that in the presence of a magnetic field in the Voigt configuration, there is inhomogeneous broadening from the DP term and the spin R/D time is finite, although much longer than that in (001) QWs.27 A thorough many-body investigation on n-type GaAs (001) QWs is performed with all the scattering explicitly included17 when the temperature is higher than 120 K. It is shown that in QW with small well width, the spin R/D time increases with the temperature in stead of decreases as predicted from the single-particle approach when the electron density is in the order of \( 10^{11} \text{ cm}^{-2} \). This temperature dependence is in good agreement with the experimental result by Malinowski et al.5 For larger well width, the situation may become different. Weng and Wu calculated the spin R/D for larger well widths by including the multi-subband effect.28 It is shown that for small/large well width so that the linear/cubic term in Eq. (2) is dominant, the spin R/D time increases/decreases with the temperature. This is because with the increase of temperature, both the inhomogeneous broadening and the scattering get enhanced. The relative importance of these two competing effects is different when the linear/cubic term is dominant.28 As the Coulomb scattering is included to orders of all the bubble diagrams, one is able to calculate the spin R/D far away from the equilibrium. It is shown in Ref. 17 that the spin R/D time increases dramatically with the spin polarization. This is discovered due to the lowest order (HF) contribution of the Coulomb interaction which appears in the coherent term of the KSBEs. With high spin polarization, the HF term serves as an effective magnetic field along the z axis which blocks the spin precession. It is further shown in Ref. 18 that after some tricks in the numerical scheme, one is able to calculate the spin R/D in the presence of a high in-plane electric field so that the system is in the hot-electron regime. It is shown that in the presence of an in-plane electric field, electron spin can precess in the absence of any magnetic field at high temperature. This
is understood that the in-plane electric field induces a center-of-mass shift of the momentum which gives rise to an effective magnetic field proportional to the electric field.\textsuperscript{18} The effect of strain on the spin R/D is also discussed and it is shown that one can effectively manipulate the spin R/D time by strain.\textsuperscript{29} Cheng and Wu further discussed the spin R/D under identical Dresselhaus and Rashba terms.\textsuperscript{30} A finite spin R/D time is obtained due to the cubic term in Eq. (2). Very recently, Zhou et al.\textsuperscript{30} extended the theory to the regime of very low temperature by figuring out ways to deal with the electron-AC phonon scattering numerically. An excellent agreement with experiment by Ohno et al.\textsuperscript{6} is obtained from 20 K to 300 K without any fitting parameter. The Dresselhaus coupling parameter $\gamma$ is found to be well represented by $\gamma = (4/3)(m^*/m_0)(1/\sqrt{2m^*/m_0}E_g)(\eta/\sqrt{1-\eta/3})^{12}$ with $m_0$ denoting the free electron mass, $E_g$ being the band gap and $\eta = \Delta/(\Delta + E_g)$. $\Delta$ is the SOC of the valence band. Moreover, a footprint of the Coulomb scattering on the spin R/D is predicted at low temperature when the electron density is not too high and the impurity density is low.\textsuperscript{30} Liu et al. applied the KSBEs to study the heavy and light holes in (001) GaAs QWs\textsuperscript{31} where the SOC is due to the Rashba term\textsuperscript{32} and is very strong so that the system is in the weak scattering limit. Therefore the single-particle formula Eq. (1) fails and only the KSBE approach is applicable. It is shown that in the weak scattering limit, adding a new scattering, such as the Coulomb scattering provides an additional spin R/D channel so that the spin R/D time is shorter.\textsuperscript{31} This is in opposite to the case of the strong scattering limit.\textsuperscript{18,31} Finally, it is pointed out in Ref. 33 that due to the strong Coulomb scattering, $T_1 = T_2 = T_3$ is valid over a very wide temperature and density regime.

IV. SPIN DIFFUSION/TRANSPORT

By solving the KSBEs together with the Poisson equation self-consistently, one is able to obtain all the transport properties such as the mobility, charge diffusion length and spin diffusion/injection length without any fitting parameter. It was first pointed out by Weng and Wu\textsuperscript{19} that the drift-diffusion equation approach is inadequate in accounting for the spin diffusion/transport. It is important to include the off-diagonal term $\rho_{k \uparrow \downarrow}$ in studying the spin diffusion/transport. With this term, electron spin precesses along the diffusion and therefore $\mathbf{k} \cdot \nabla \rho_{k \uparrow \downarrow}(\mathbf{r}, t)$ in the diffusion term offers an additional inhomogeneous broadening. With this additional inhomogeneous broadening, any scattering, including the Coulomb scattering, can cause an irreversible spin R/D.\textsuperscript{19} Unlike the spin precession in the time domain where the inhomogeneous broadening is determined by $\hbar(\mathbf{k})$, here it is determined by $|\mu_B \mathbf{B} + \hbar(\mathbf{k})|/k_T$ provided the diffusion is along the $x$-axis. Therefore, even in the absence of the DP term, the magnetic field alone can provide an inhomogeneous broadening.\textsuperscript{19} Moreover, it is first pointed out that a spin pulse can oscillate along the diffusion in the absence of the magnetic field at very high temperature.\textsuperscript{20} Detailed study is performed later on this effect.\textsuperscript{21,22} This oscillation was later realized experimentally by Crooker and Smith\textsuperscript{7} in bulk system at very low temperature. It is also shown that the Coulomb drag plays a very important role in the spin diffusion and the electric field can enhance/suppress the spin diffusion.\textsuperscript{22} Very recently Cheng and Wu developed a new numerical scheme to calculate the spin diffusion/transport\textsuperscript{34} with very high accuracy and speed. It is discovered that due to the scattering, especially the Coulomb scattering, $T_2 = T_3^* = T_3$ is valid even in the space domain. Moreover, as the inhomogeneous broadening in spin diffusion is determined by $|\hbar(\mathbf{k})|/k_T$ in the absence of magnetic field, the period of the spin oscillations along the $x$-axis is independent on the electric field\textsuperscript{34} which is different from the spin precession rate in the time domain.\textsuperscript{18} This is consistent with the experimental findings by Beck et al.\textsuperscript{7} Many properties of the spin diffusion/transport in the steady state are addressed in detail in Ref. 34.

V. SUMMARY

In summary we reviewed our fully microscopic KSBE investigate on spin R/D in the spin precession and spin diffusion/transport. The importance of the Coulomb scattering is stressed. This approach allows one to deal with systems both near and far away from the equilibrium and in both the strong and weak scattering limits. Moreover, both the effect of inhomogeneous broadening on the scattering and the counter effect of the scattering on the inhomogeneous broadening are fully accounted.

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\textsuperscript{1} Optical Orientation, edited by F. Meier and B. P. Zakharchenya, (North-Holland, Amsterdam, 1984).
