Optically-Induced Suppression of Spin Relaxation in Two-Dimensional Electron Systems with Rashba Interaction

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A pulsed technique for electrons in 2D systems, in some ways analogous to spin echo in nuclear magnetic resonance, is discussed. We show that a sequence of optical below-band gap pulses can be used to suppress the electron spin relaxation due to the D'yakonov-Perel' spin relaxation mechanism. The spin relaxation time is calculated for several pulse sequences within a Monte Carlo simulation scheme. The maximum of spin relaxation time as a function of magnitude/width of the pulses corresponds to $\pi$-pulse. It is important that even relatively distant pulses efficiently suppress spin relaxation.

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There has been a lot of experimental and theoretical interest in the physics of spin relaxation in semiconductor structures. The main reason for that is the potential of spintron applications. Controlling spin relaxation rate is interesting both from a fundamental and practical point of view. One of the ways through which spin polarization can be lost is spin-orbit interaction. Of particular interest is Rashba spin-orbit (SO) interaction, which is observed in asymmetric heterostructures. Corresponding spin relaxation mechanism is known as D'yakonov-Perel' (DP) spin relaxation mechanism.

Let us consider a system of 2D electrons confined in a quantum well or heterostructure. The Rashba spin-orbit interaction can be regarded as an effective momentum-dependent magnetic field acting on electron spins. In the presence of the effective magnetic field, the electron spins feel a torque and precess in the plane perpendicular to the magnetic field direction with an angular frequency $\Omega(k)$. This precession leads to an average spin relaxation (dephasing). Momentum scatterings reorient the direction of the precession axis, making the orientation of the effective magnetic field random and trajectory-dependent. Therefore, frequent scattering events suppress the precession and consequently the spin relaxation. This is the motional-narrowing behavior, accordingly to which the spin relaxation time $\tau_s^{-1} \propto \tau_p^{\frac{1}{2}}$, where $\tau_p$ is a momentum scattering time.

Spin echo is a standard way to overcome dephasing in nuclear magnetic resonance experiments. Nuclear spin magnetization, after a free induction decay, can be restored, as a result of the effective reversal of the dephasing of the spins (refocusing) by the application of a refocusing RF pulse (applied in a time shorter than or of the order of $T_2^*$ time). Unfortunately, this method can not be directly applied to electron spin coherence in heterostructures. One of the obstacles is that the minimum achievable RF pulse length of $\sim 10$ ns is of the order or even longer than the typical spin coherence time. Moreover, the effective magnetic field due to SO interaction is fixed only between two consecutive scattering events. Therefore, a refocusing pulse sequence should have a pulse separation of the order of $\tau_p$ and pulse duration much shorter than $\tau_p$. In what follows we discuss a possible realization of such refocusing pulse sequence based on a method from femtosecond optics.

In this Letter we consider dynamics of electron spin polarization in a two-dimensional semiconductor structure like a quantum well or heterostructure under a train of intense optical below-band gap circularly-polarized pulses. Recent experiments have been demonstrated that an effective magnetic field due to an optical below-band gap pulse coherently rotates electron spins on a time scale of $\sim 150fs$, which is much shorter than typical values of $\tau_p$ in clean structures. The mechanism of spin rotation is based on the optical Stark effect. Physically, the optical Stark effect in semiconductors is related to optically-induced modification (dressing) of quantum states, including optically-induced spin splitting. Since below-band gap laser does not excite real excitons, the optically-induced spin splitting lasts only as long as the pump pulse. The purpose of the current investigation is to study the effect of the pulse sequence on electron spin relaxation time in 2D quantum structures with dominant D'yakonov-Perel' spin relaxation mechanism.

Let us consider the evolution of an electron spin (initially aligned with $z$-axis) during a time interval between two consecutive scattering events. Using a semiclassical approach to electron space motion (the electrons are treated as classical particles in the effective-mass approximation), we assume that an electron moves along a straight trajectory with a constant velocity. Fig. 1(a) shows that without a pulse, the direction of electron spin at $t = t_0$ is changed by an angle $\theta$ due to precession around the effective spin-orbit magnetic field $B_R$. Fig. 1(b) demonstrates the effect of the light pulse applied at $t = t_0/2$ (Fig. 1(c)) with such a width and intensity that the electron spin rotates around $z$-axis by angle $\pi$. The main idea of our approach is illustrated in Fig. 1(b).
It is readily seen that in this case at $t = t_0$ the electron spin is directed in the initial $z$-direction, so the effect of Rashba spin-orbit interaction is eliminated. In reality, of course, it is not possible to apply pulses exactly in the middle of each free flight interval for each electron, hence, a residual relaxation remains.

In order to get a quantitative estimation of the effect, we perform a Monte Carlo simulation of spin dynamics in the presence of optical below-band gap pulses. The electron spin relaxation time is calculated as a function of the electron spin precession angle $\varphi$ (due to a pulse) for different selected values of the spacing between pulses $T_B$ and for two types of pulse sequences: unidirectional and alternating. For the sake of simplicity, we assume that the effective magnetic field due to the pulse is much stronger than the effective magnetic field due to the spin-orbit interaction. This assumption allows us to consider the electron spin precession events due to the pulses as instantaneous.

Within a Monte Carlo simulation scheme, it is assumed that the electrons move along trajectories, which are defined by bulk scattering events (scattering on phonons, impurities, etc.), with an average velocity $\mathbf{v}$. The angular frequency corresponding to the Rashba coupling can be expressed as $\Omega = \eta \vec{\mathbf{d}} \times \hat{z}$, where $\eta = 2\alpha m^* \hbar^{-2}$, $m^*$ is the effective electron mass, and $\alpha$ is the interaction constant that enters into the Rashba spin-orbit coupling Hamiltonian

$$H_R = \alpha \hbar^{-1} (\sigma_x p_y - \sigma_y p_x).$$

(1)

Here, $\sigma$ is the Pauli-matrix vector corresponding to the electron spin. The spin of a particle moving ballistically over a distance $1/\eta$ will rotate by the angle $\gamma = 1$. The angle of the spin rotation per mean free path $L_p$ is given by $\eta L_p$. It is assumed that at the initial moment of time the electron spin is polarized in $z$-direction (perpendicular to the plane) by a pump beam. We calculate $\langle S \rangle$ as a function of time by averaging over an ensemble of electrons and taking into account both Rashba-induced and optically-induced spin precessions. The spin relaxation time is evaluated by fitting the time-dependence of $\langle S \rangle$ to an exponential decay. The detailed description of the basic Monte Carlo simulation scheme can be found in Ref. [8]. We note that the selected Monte Carlo algorithm correctly describes the physics of DP relaxation. However, since all scattering parameters and temperature effects are taken into account only via two parameters $L_p$ and $\tau_p$, the temperature dependence as well as the role of Coulomb scattering can not be easily evaluated, and more sophisticated simulations [13] are required.

The time-dependence of $\langle S \rangle$ was calculated for an ensemble of $10^5$ electrons for each value of the parameters describing the pulse sequence. The spin relaxation time for various pulse spacings is shown in Fig. 2 as a function of the spin rotation angle. We found that the rate of increase of spin relaxation time does not depend on the parameter $\eta L_p$ when $\eta L_p < 1$. Instead, it is completely defined by the spacing between pulses, by the type of pulse sequence, and by the spin rotation angle due to a pulse. A strong dependence of the spin relaxation time on the pulse sequence is observed. For short spacings between pulses, the unidirectional pulse sequence suppresses the spin relaxation more efficiently than the alternating pulse sequence. The spin relaxation time coincides for both pulse sequences only for $\varphi = n\pi$, where $n$ is an integer number. Furthermore, the spin relaxation time $\tau_n(\varphi)$ is a periodic function of $\varphi$ with period $2\pi$, symmetric within a period, $\tau_n(\varphi + \beta) = \tau_n(\varphi - \beta)$, where $\beta \in [0, \pi]$, and has a maximum at $\varphi = \pi(2n + 1)$. By increasing the spacing between pulses, the relaxation time decreases for both sequences. When the spacing between pulses becomes as long as a few momentum relaxation times, the spin rotations due to neighboring pulses become uncorrelated and the dependence of the spin relaxation time on $\varphi$ is the same for both pulse sequences. This is clearly seen for $T_B = 3\tau_p$ in Fig. 2. It is important to notice that a significant increase of spin relaxation time is observed even when the spacing between pulses is longer than $\tau_p$.

Fig. 3 shows the spin relaxation time as a function of the spacing between pulses $T_B$ in the practically important situation $\varphi = \pi$, which is characterized by the longest spin relaxation time. The spin relaxation time sharply increases at small values of $T_B$ and slowly decreases with increase of $T_B$ to the spin relaxation time without pulses $\tau_s(\varphi = 0)$. Let us derive the asymptotic behavior of the spin relaxation time as a function of spacing between pulses in this case. First, consider the limit of distant pulses, when $T_B \gg \tau_p$. Using a method described in Ref. [30] and assuming that a pulse is applied in an arbitrary time moment $t$ between two scattering events separated by a time interval $\tau$, the mean squared dephasing between these scattering events $\langle \delta \theta^2 \rangle$ is given by

$$\langle \delta \theta^2 \rangle = \frac{1}{n} \int_0^\tau \langle \Omega \rangle^2 (2t - \tau)^2 dt = \frac{1}{3} \langle \Omega \rangle^2 \tau^2.$$  

(2)

The mean squared dephasing between two scattering
FIG. 2: Spin relaxation time as a function of the spin precession angle $\phi$ due to a pulse for several pulse periods $T_B$ and two types of pulse sequences: unidirectional pulse sequence (a), alternating pulse sequence (b). These plots were obtained using the parameter value $\eta L_p = 0$.

4. events without a pulse is simply given by $\delta \theta^2 = \Omega^2 \tau^2$. Taking into account the pulse probability, $\tau/T_B$, and the exponential distribution of probability of scattering, $p(\tau, \tau + d\tau) = (1/\tau_p) \exp(-\tau/\tau_p) d\tau$, the mean free dephasing after $\delta \theta^2$ scattering events will be

$$\delta \theta^2 = \frac{1}{\tau_p} \int_0^\infty e^{-\tau/\tau_p} \left( \left( 1 - \frac{\tau}{T_B} \right) + \frac{\tau}{T_B} \right) \Omega^2 \tau^2 d\tau = 2n\Omega^2 \tau_p^2 \left( 1 - \frac{\tau_p}{T_B} \right).$$ (3)

If we take the relaxation time $\tau_s$ for a group of spins in phase at the initial moment of time to get about one radian out of step, we find

$$\tau_s = \frac{\tau_p}{2\Omega^2 \tau_p^2} \left( 1 - \frac{\tau_p}{T_B} \right).$$ (4)

The asymptotic expressions for spin relaxation time, Eqs. (4), (5) are presented in Fig. 3 showing an excellent agreement with Monte Carlo results.

The first term at the right-hand side of Eq. (4) is the spin relaxation time without pulses, the second term describes the effect of the pulse sequence. In the opposite limit, when the number of pulses per mean free path is large $T_B \ll \tau_p$, the spacing between pulses $T_B$ defines the characteristic angle of spin precession between two scattering events, instead of the momentum relaxation time $\tau_p$. Thus we can write

$$\tau_s \sim \frac{\tau_p}{\Omega^2 T_B}. \quad (5)$$

The asymptotic expressions for spin relaxation time, Eqs. (4), (5) are presented in Fig. 3 showing an excellent agreement with Monte Carlo results.

We would like to emphasize that the proposed technique is most suitable for clean quantum structures with low electron density at low temperatures, i.e. when $\tau_p$ is long. For example, taking $v_F = 5 \cdot 10^6$ cm/sec and $L_p = 1$ $\mu$m we obtain $\tau_p = 20$ ps. Our calculations indicate that in order to get a two-fold increase in $\tau_s$, the spacing between the pulses at $\tau_p = 20$ ps should be $\sim 50$ ps at $\varphi = \pi$. The calculations presented in this paper have been made for a particular value of the parameter $\eta L_p = 0.4$. This specific value of $\eta L_p$ is realizable in physical systems. For instance, considering an InAlAs/InGaAs quantum well [31] with $\alpha = 0.4 \cdot 10^{-12}$ eV m, $m^* = 0.04 m_e$, and $L_p = 1$ $\mu$m, we obtain $\eta L_p = 0.42$. We would like to emphasize again that the rate of change of $\tau_s$ does not depend on $\eta L_p$ in the motional-narrowing regime.

In order to experimentally observe suppression of spin relaxation, the energy of below-band gap laser must be adjusted to minimize the excitation of real carriers by compromising between state-filling effects and magnitude of the Stark shift [27]. Recent calculations for quantum dot geometry demonstrate that $\pi$ pulses may be obtained...
The pulse sequence rotating electron spins around the axis perpendicular to the quantum well significantly suppress spin relaxation in a way quite similar to the spin echo in the nuclear magnetic resonance. The spin rotation mechanism is based on the optical Stark effect. It was demonstrated that the optical Start effect in semiconductors allows obtaining very short (∼150fs) and strong (∼20T) pulses of effective magnetic field [27].

Spin relaxation time was calculated for different pulse sequences and spacing between pulses. It was found that, in general, unidirectional pulse sequences suppress the spin relaxation more efficiently than the alternating one. Analytical formulae for asymptotic behavior of the spin relaxation time were obtained. The proposed method of spin coherence control could find applications in probing spin-coherence dynamics in heterostructures.

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