Spin Relaxation in Si Quantum Wells Suppressed by an Applied Magnetic Field

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We investigate spin properties of the two-dimensional electron gas in Si quantum wells defined by SiGe barriers. We find, in contrast to predictions of the classical model of D'yakonov-Perel, a strong anisotropy of spin relaxation and a decrease of the spin relaxation rate with increasing electron mobility. We show that for high electron mobility the cyclotron motion causes an additional modulation of spin-orbit coupling which leads to an effective suppression of spin relaxation rate.

In spintronics, the aim is to make use of the spin degrees of freedom in addition to the electronic ones. Therefore, spintronic devices based on spins of carriers in semiconductors appear particularly promising. In such elements carriers can be easily moved by applying external voltages, the well known tool of classical electronics. The utilization of spin properties, however, usually is limited by the fast spin relaxation of conduction electrons. Therefore analysis of the spin relaxation mechanisms and the search for a suitable material and optimum conditions are of primary interest in this field. In III-V compounds the spin relaxation time is below one nanosecond [1]. Silicon based devices, due to much weaker spin-orbit coupling, appear much more promising.

2D Si layers in Si/SiGe structures exhibit a spin relaxation time of the order of a few microseconds by measurements of electron spin resonance (ESR) [2] – [5]. We also proved that the Bychkov-Rashba (BR) spin-orbit coupling [6] is the main origin of spin relaxation in one sided modulation doped quantum wells with high mobility [5]. We also found an anisotropy of the line width which implies an anisotropy of the transverse spin relaxation time of more than an order of magnitude whereas the usual theory can explain only a factor of two. In this work we show that motional narrowing due to the cyclotron motion is an important ingredient in the understanding of the transverse spin relaxation time in high mobility systems and the same holds for the longitudinal one.

The effect of BR coupling on spin, $\boldsymbol{\sigma}$, of a conduction electron can be described by an effective magnetic field, $\mathbf{B}_{BR}$. This field is oriented in-plane and perpendicular to electron momentum, $\hbar\mathbf{k}$. The resulting zero field splitting is given by: $\Omega_{BR} = g\mu_B \mathbf{B}_{BR} \cdot \boldsymbol{\sigma}$.

The direction of the BR field depends on the direction of electron k-vector, and therefore the spread of k-vectors results in a spread of the BR field. Consequently, the ESR resonance is shifted and broadened. Momentum scattering, described by a rate $1/\tau_k$, causes a modulation of the BR field in time which leads to the so called D'yakonov-Perel (DP) spin relaxation [7]. Modulation of the BR field leads to motional narrowing of the spread of BR field. The narrowed linewidth, i.e., the spin decoherence rate, $1/T_2$, is thus expected to be proportional to τ_k. Also the longitudinal spin relaxation rate, $1/T_1$, (the inverse spin lifetime, T_1) is predicted to be proportional to τ_k. The DP model explains the ESR frequency shift and the linewidth well for an external magnetic field directed in sample plane [5]. For an electron concentration of the order of a few times 10^{11} cm^{-2} the (unnarrowed) BR field is of the order of 100 G.

The total line width caused by BR field, predicted by the classical DP mechanism, is expected to be isotropic [8]. In spite of that, the observed linewidth is strongly anisotropic. Sample data for the anisotropy of the ESR linewidth are given in Fig. 1. For perpendicular orientation of the magnetic field, $\theta = 0°$, the linewidth, $\Delta\omega(0°)$, is by an order of magnitude smaller as compared to in-plane orientation, $\Delta\omega(90°)$. The anisotropy ratio, $\Delta\omega(90°)/\Delta\omega(0°)$, increases with increasing electron mobility and reaches a value of about 1.5 for $\tau_k^{-1} = 10^{12}$ s^{-1} and increases up to 10 for $\tau_k^{-1} = 5 \cdot 10^{10}$ s^{-1}.

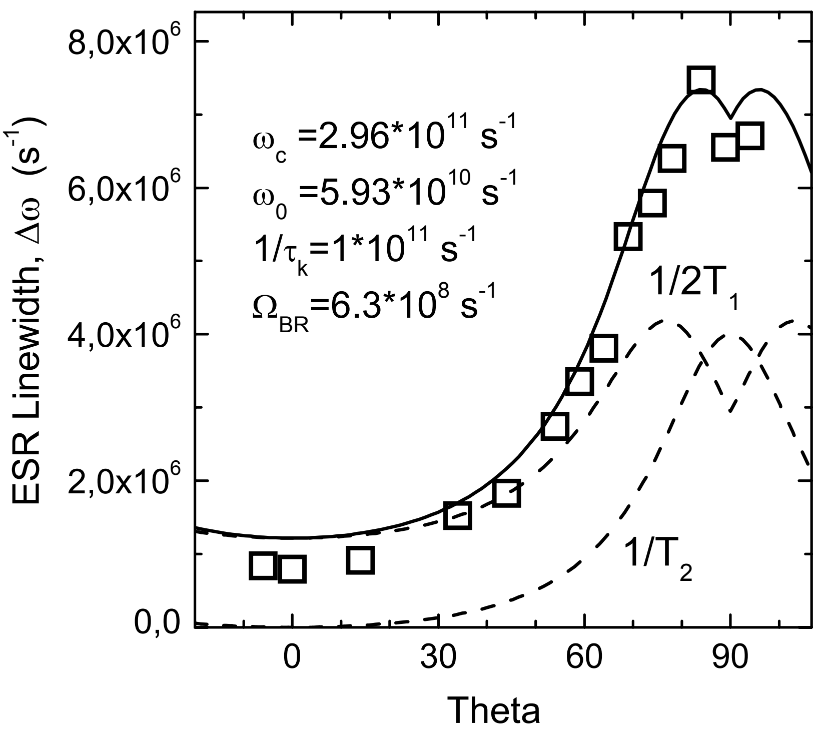

Fig. 1: Dependence of the ESR linewidth of conduction electrons in a 2D Si/SiGe structure on the direction of applied magnetic field. $\theta = 0$ stands for perpendicular direction to the layer. The solid line describing the linewidth corresponds to Eq. (4), while the transverse and longitudinal components are marked by dashed lines and described by Eqs (3, 4)

To explain the observed peculiarities we consider the influence of the cyclotron motion on the spin relaxation. In an external magnetic field, **B**, the curvature of the cyclotron trajectory is equivalent to a change of the BR field. As a consequence, the BR field is additionally modulated leading to a suppression of the spin relaxation. The cyclotron frequency of 2D electrons, ω_c, scales with the perpendicular component of the applied field, $B \cdot \cos\theta$. Therefore, the effective modulation frequency, and the resulting spin relaxation rate also depend on θ.

According to general rules, both components of spin relaxation are ruled by Fourier components of the correlation function of the perturbing field [9]. Momentum scattering and cyclotron motion lead to the following correlation function of the BR perturbation:

$$C(\tau) = \langle \mathbf{\Omega}_{BR}(\tau), \mathbf{\Omega}_{BR}(0) \rangle = \Omega_{BR}^2 \exp\left(i\omega_c \tau - \frac{\tau}{\tau_k} \right) \qquad (1)$$

The resulting expressions for the longitudinal and the transverse spin relaxation rates take the form:

$$\frac{1}{T_1} = \Omega_{BR}^2\left(1+\cos^2\theta\right)\frac{\tau_k}{1+\left(\omega_0-\omega_c\right)^2\tau_k^2} \tag{2}$$

$$\frac{1}{T_2} = \Omega_{BR}^2\frac{\sin^2\theta}{2}\frac{\tau_k}{1+\omega_c^2\tau_k^2} \tag{3}$$

Here ω_0 is the Larmor frequency and $\Omega_{BR}^2\left(1+\cos^2\theta\right)$ is the variance of the perpendicular component of the BR field and $\Omega_{BR}^2\sin^2\theta$ its longitudinal component.

The total linewidth is:

$$\Delta\omega = \frac{1}{2T_1}+\frac{1}{T_2} \tag{4}$$

The lines in Fig. 1 correspond to Eqs. (2) – (4). The observed angular dependence is well described. The characteristic maximum of the linewidth, which occurs at $\theta \cong 80^\circ$, corresponds to a resonance- like condition at $\omega_0 \cong \omega_c$, where the energy of the cyclotron motion can be transferred to the spin system. Ω_{BR} is the only fitting parameter, but the anisotropy ratio does not depend on Ω_{BR}. In that sense, the theoretical prediction of the suppression of the spin relaxation, equivalent to the anisotropy ratio, is described without any fitting parameter.

The present model implies also a strong dependence of the suppression of spin relaxation on the electron mobility. For low mobility, $\omega_c\tau_k << 1$, Eqs.(2) and (3) take the classical form. The DP relaxation rate is expected to be proportional to the momentum relaxation time. The spin relaxation rate thus should increase with increasing mobility. For $\omega_c\tau_k > 1$, however, the opposite dependence is expected for the spin relaxation rates according to Eqs. (3) and (4): here the higher mobility leads to slower spin relaxation.

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