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WEAK ANTILOCALIZATION IN QUANTUM WELLS

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Spin relaxation in degenerated two-dimensional (2D) electron gas is studied by measurements of the magnetic field dependence of the weak antilocalization corrections to the conductivity in GaInAs quantum wells. Consistent quantitative (up to order of magnitude) description of weak antilocalization data on GaAs like heterojunctions and quantum wells was obtained. Our results show that spin precession around the effective magnetic field direction as described by the Dyakonov–Perel model is the main spin relaxation mechanism in degenerated 2D electron gas in semiconductors with no inversion symmetry.

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1. Quantum corrections to the conductivity

Weak localization comes from the constructive interference of two time reversal paths of electrons scattered in the disordered systems. It leads to the quantum reduction of the conductance. However, in the presence of strong spin scattering, the two time reversal paths can give rise to destructive interference and enhance the conductance. This phenomenon is called weak antilocalization. Magnetic field destroys both the spatial and the spin interferences. Therefore, with increasing magnetic field one can observe low field positive magnetoresistance (weak antilocalization feature) followed by negative magnetoresistance (weak localization feature).

In this section we present the main results of the theory of quantum corrections to the conductivity due to weak antilocalization. More detailed derivations are presented in Ref. [1]. The quantum corrections to the conductivity $\Delta\sigma(B)$ can be expressed by the formula

$$\Delta\sigma(B) = -\frac{e^2}{\pi h}\left[\psi\left(\frac{1}{2}+\frac{H_{\mathrm{tr}}}{B}\right) - \psi\left(\frac{1}{2}+\frac{H_2}{B}\right) + \frac{1}{2}\psi\left(\frac{1}{2}+\frac{H_\phi}{B}\right) - \frac{1}{2}\psi\left(\frac{1}{2}+\frac{H_4}{B}\right)\right], \quad (1)$$

where

$$\Delta\sigma(0) = -\frac{e^2}{\pi h}\left[\ln\left(\frac{H_{\mathrm{tr}}}{H_2}\right) + \frac{1}{2}\ln\left(\frac{H_\varphi}{H_4}\right)\right],$$

B is the magnetic field, $\psi(x)$ is the digamma function defined by

$$\psi(x) = \sum_{n=1}^{\infty}\frac{x}{n(x+n)}, \qquad H_2 = H_\varphi + H_{\mathrm{so}}, \qquad H_4 = H_\varphi + 2H_{\mathrm{so}}.$$

The characteristic transport H_{tr}, phase H_φ and H_{so} magnetic fields are related to the corresponding relaxation times τ_{tr}, τ_φ, τ_{sx} by

$$H_{\mathrm{tr}} = \frac{\alpha}{\tau_1}, \qquad H_\varphi = \frac{\alpha}{\tau_\varphi}, \qquad H_{\mathrm{so}} = \frac{\alpha}{\tau_{sx}}, \qquad \alpha = \frac{\hbar}{4eD}, \quad (2)$$

where D is the diffusion constant. Formula (1) is as Hikami–Larkin–Nagaoka formula [2] but the definition of H_{so} is different by a factor 2.

In the Dyakonov–Perel mechanism the spin relaxation is due to the spin precession around the effective magnetic field. This field depends on the electron wave vector and changes due to scattering. For 2D electron gas τ_{sx}^{-1}, the spin relaxation rate of the x component of the spin, can be written [1] as a sum of two contributions which corresponds to two spin precessions with frequencies ω_1, ω_3 and corresponding relaxation times τ_1 and τ_3:

$$\frac{1}{\tau_{sx}} = \frac{1}{2}\left(\omega_1^2\tau_1 + \omega_3^2\tau_3\right). \quad (3)$$

τ_1, τ_3 are defined by

$$\frac{1}{\tau_n} = \int W(\theta)(1-\cos n\theta)\mathrm{d}\theta,$$

where $W(\theta)$ is the probability of the change of the electron wave vector direction by the angle θ in unit time due to elastic scattering. Precession frequencies can be expressed as

$$\omega_1^2 = \frac{4a_{42}^2}{\hbar^2} k_\mathrm{p}^2 \left(\langle k_z^2 \rangle - \frac{k_\mathrm{p}^2}{4} \right)^2,$$

$$\omega_3^2 = \frac{4a_{42}^2}{\hbar^2} \frac{k_\mathrm{p}^6}{16},$$

k_p and k_z are respectively in-plane and z component of the wave vector, a_{42} is the band structure constant [3]. Formal derivation of the relation (3) can be found in Ref. [1].

Using relations (2) and (3), replacing k_p by k_f because for degenerated electron gas only electrons at the Fermi surface play role and expressing the diffusion constant D for the degenerate 2D gas as

$$D = \frac{1}{2} \left(\frac{\hbar k_\mathrm{f}}{m^*} \right)^2 \tau_1,$$

we finally get the expression for the characteristic spin relaxation field H_so which is usually determined in the weak antilocalization experiments

$$H_\mathrm{so}(N_\mathrm{s}) = \frac{\eta}{(2\pi)^2} \left(\frac{1 + \tau_3/\tau_1}{2} k_\mathrm{f}^4 - 4\langle k_z^2 \rangle k_\mathrm{f}^2 + 8\langle k_z^2 \rangle^2 \right), \quad (4)$$

where $k_\mathrm{f}^2 = 2\pi N_\mathrm{s}$.

Coefficient

$$\eta = \frac{\pi m^{*2}}{4e\hbar^3} a_{42}^2$$

was chosen to have the same meaning as in Ref. [4].

2. Experimental

Two AlGaAs/InGaAs/GaAs pseudomorphic quantum wells were studied. They were grown by the molecular beam epitaxy technique. The layer sequence of the structure were of the standard HEMT type [5]. Both samples were δ-doped with Si (doping density $N_\delta = 2.5 \times 10^{12}$ cm^{-2}).

In order to study the behavior of the structures as a function of N_s, the metastable properties of the DX Si centers present in AlGaAs-layer were used. This allowed to tune carrier density from 1.06×10^{12} /cm^2 to 1.29×10^{12} /cm^2 for sample A and from 1.52×10^{12} /cm^2 to 2.05×10^{12} /cm^2 for sample B.

We used a system of two superconducting coils (8 T/8 T) placed in the same cryostat — the scattered field of one coil was compensated by another one allowing to get good tunability and uniformity of the magnetic field in the sample space. The same system was earlier used to study cyclotron emission from different semiconductors systems and is described in more detail in Ref. [6].

3. Results and discussion

Quantitative analysis of the data was performed on the basis of formula (1). H_{tr} was determined by transport measurements of carrier density and mobility. Usually parameters H_{so} and H_{φ} should be determined by fitting formula (1) to the experimental results. One can improve this by fitting not only the conductivity but also its first derivative. Figure 1 shows example of the data and its derivative and results of fit.

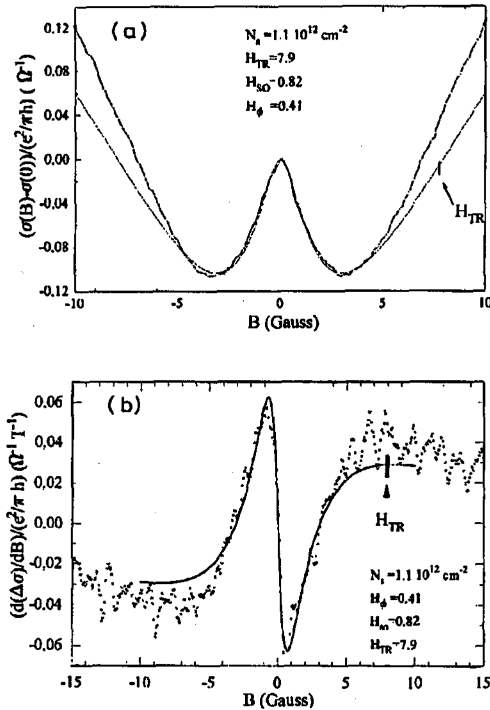

Fig. 1. Example of fit of formula (1) (a) and its first derivative (b) to the experimental results.

In Fig. 2 dependence of the H_{so} on the carrier density is showed. Continuous lines are results of the calculation according to (4). For value a_{42} we took 24 eV Å^3 as found in measurements of spin relaxation by optical orientation [7] and band-structure calculations [3] for GaAs. The effective mass m^* was set at $0.067m_0$ as determined by cyclotron resonance emission measurements performed on the same samples [5]. Value of $\langle k_z^2 \rangle$ was obtained from self-consistent Poisson–Schrödinger calculations.

Special feature of the $H_{so}(N_s)$ dependence for quantum wells is that H_{so} starts from important value for $N_s = 0$ and then decreases reaching minimum. Because the experimentally determined value of H_{so} increases with N_s, beginning from about 1.2×10^{12} /cm^2 one can state that at least for higher concentrations

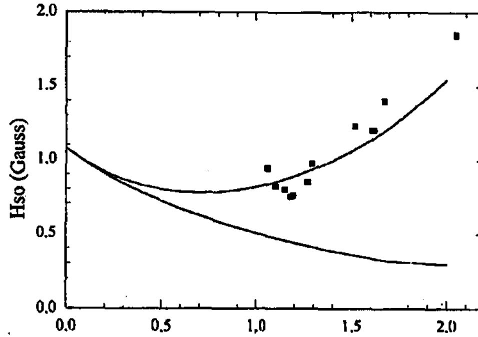

Fig. 2. Quantum well: H_{so} as a function of the carrier density N_s theory and experiment. Theoretical results are presented in two limit cases: short range scattering ($\tau_1 = \tau_3$, upper curve) and long range scattering ($\tau_1 = 9\tau_3$, lower curve).

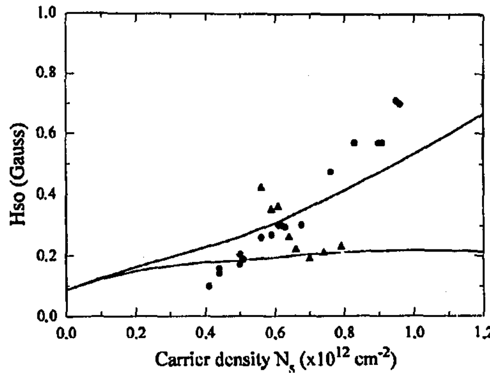

Fig. 3. Heterojunction: H_{so} as a function of the carrier density N_s theory and experiment — results of Ref. [1] (points) and Ref. [10] (triangles). Upper and lower curve as in Fig. 2.

the dominating elastic scattering mechanism is an isotropic one. Possible scattering mechanisms could be alloy scattering or scattering due to the interface roughness.

The presented theory can be also applied to interpreting experimental results of other authors [4, 8]. The main difference is that all existing antilocalization data were taken for heterojunctions and not quantum wells. In the case of heterojunctions $\langle k_z^2 \rangle$ depends much stronger on the carrier density. On the base of the presented theory we calculated $H_{so}(N_s)$ for the case of heterojunctions. Comparison of the theoretical results with experimental data of Ref. [4] and [8] is shown in Fig. 3.

4. Conclusion

Spin relaxation in 2D systems was studied. Theoretical approach taking into account spin relaxation according to different precession movements with their

appropriate relaxation times was presented. We show that if all elements are properly taken into account one can get good consistent quantitative (up to order of magnitude) description of the all existing experimental data without any fitting parameters. This allows to state that the spin precession as described by the Dyakonov and Perel model is the main spin relaxation mechanism in the 2D systems with no inversion symmetry.

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