Antilocalization in gated 2D quantum well structures with composition gradient

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Abstract

Low-field magnetoconductivity caused by the quantum interference is studied in the gated 2D quantum well structures with the composition gradient. It is shown that the Dresselhaus mechanism well describes an antilocalization minimum on the conductivity-magnetic field curve.

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I. INTRODUCTION

An asymmetry of the quantum well leads to splitting of the energy spectrum due to spin-orbit interaction. The inversion asymmetry of the crystal field results in linear and cubic in quasimomentum terms in the energy spectrum and thus leads to so called Dresselhaus spin-orbit splitting. The dispersion law for the heterostructure grown in [001] direction looks in this case as follows

\[ E(k, \varphi) = \frac{k^2}{2m} \pm \sqrt{\Omega_1^2 + \Omega_2^2 + 2\Omega_1\Omega_3 \cos(4\varphi)}, \] (1)

where \( \Omega_1 = \gamma k ((k_z^2) - k^2/4), \) \( \Omega_3 = \gamma k^3/4, \) \( k^2 = k_x^2 + k_y^2, \) \( \tan \varphi = k_x/k_y, \) \( (k_z^2) \) is the mean square of electron momentum in the direction perpendicular to 2D plane, and \( \gamma \) is the constant of spin-orbit interaction, which depends on the band parameters of the bulk material.

An asymmetry of smooth electrostatic potential in the perpendicular to the 2D plane direction due to Schottky barrier or due to asymmetry in disposition of doping layers gives linear term or, so called, the Rashba term

\[ E(k) = \frac{k^2}{2m} \pm \Omega_R, \] (2)

where \( \Omega_R = \alpha |k| \). The value of parameter \( \alpha \) can be found within framework of \( kP \)-formalism:

\[ \alpha = \frac{P^2}{3} \left( \Psi(z) \left| \frac{d}{dz} \left( \frac{1}{E_F - E_{\Gamma_7}(z)} - \frac{1}{E_F - E_{\Gamma_8}(z)} \right) \right| \Psi(z) \right), \] (3)

where \( \Psi(z) \) is the wave function for the confined electrons, \( P \) is the momentum matrix element, \( E_F \) is the Fermi energy, and \( E_{\Gamma_7}(z) \) and \( E_{\Gamma_8}(z) \) are the positions of the band edges energies for \( \Gamma_7 \) and \( \Gamma_8 \) valence bands, respectively, at position \( z \).

As seen from Eq. (3) an appropriate disposition of the doping layers and quantum well, in principle, gives a possibility to engineer the value of the spin splitting. Another way to change the splitting is a variation of composition within the quantum well in the growth direction.

One of suitable way to study the spin splitting of the energy spectrum at zero-magnetic field is analysis of the weak antilocalization. This paper is devoted to experimental study of the low magnetic field positive magnetoresistance caused by the spin relaxation in GaAs/In\(_x\)Ga\(_{1-x}\)As/GaAs quantum wells.
FIG. 1: Indium distribution (upper panels) and energy diagrams (lower panels) for structures 3635 (a) and 3512 (b).

II. EXPERIMENTAL DETAILS

The quantum well GaAs/In$_x$Ga$_{1-x}$As/GaAs heterostructures were grown by metal-organic vapor phase epitaxy on semi-insulator GaAs substrate. Two types of heterostructures were measured.

Asymmetric heterostructure 3635 consists of a 0.3 µm-thick undoped GaAs buffer layer, a 30 nm In$_x$Ga$_{1-x}$As well, a 15 nm spacer of undoped GaAs, a Si δ-layer and 200 nm cap layer of undoped GaAs. The concentration of In within the quantum well varies from 0.1 to 0.6 from the buffer to cap as $0.6/[6 - 0.17(z + 245)]$, where $z$ is the coordinate perpendicular to the quantum well plane, measured in nanometers [upper panel in Fig. I(a)]. The energy diagram calculated for this structure is presented in lower panel in Fig. I(a). The electron density $n$ and mobility $\mu$ are the following: $n = 8 \times 10^{15}$ m$^{-2}$, $\mu = 2.4$ m$^2$/Vs.

Heterostructures 3512 and Z76 are symmetric. The heterostructure 3512 consists of 0.5 mkm-thick undoped GaAs epilayer, a Sn δ-layer, a 9 nm spacer of undoped GaAs, a 8 nm In$_{0.2}$Ga$_{0.8}$As well, a 9 nm spacer of undoped GaAs, a Sn δ-layer, and a 300 nm cap layer of undoped GaAs. The electron density and mobility are the following: $n = 9.5 \times 10^{15}$
FIG. 2: The low-field magnetoconductance taken for different temperatures for the structure 3635 at $V_g = 0$. Symbols are the experimental data. Solid line is the best fit by ILP-formula\textsuperscript{2} with the parameters $B_{tr} = 2.4$ mT, $\tau_\phi = 7.2 \times 10^{-11}$ s, and $\tau_s = \tau'_s = 0.88 \times 10^{-11}$ s.

m$^{-2}$, $\mu = 1.4$ m$^2$/Vs. The energy diagrams for structure 3512 is presented in Fig.\textsuperscript{1}(b). The structure Z76 is analogous. The only difference is thickness of spacer between the Sn $\delta$-layers and quantum well, which is 12 nm. The parameters of this structure are $n = 6.2 \times 10^{15}$ m$^{-2}$ and $\mu = 2.4$ m$^2$/Vs.

The samples were mesa etched into standard Hall bars and then an Ag or Al gate electrode was deposited by thermal evaporation onto the cap layer through a mask. Varying the gate voltage $V_g$ we were able to control the density and conductivity of electron gas in the quantum well. The low field magnetoresistance was measured with step $10^{-2}$ mT within the temperature range 0.45 – 5.0 K.

III. RESULTS AND DISCUSSION

Figure\textsuperscript{2} shows the low-field magnetoconductivity $\sigma(B) = \rho_{xx}^{-1}(B)$ measured for the structure 3635 as a function of magnetic field $B$ for different temperatures. The antilocalization minimum in low fields, which magnitude decreases with temperature increase, is clearly seen.

The data treatment was performed using the model developed by Iordanskii, Lyanda-Geller, and Pikus (ILP)\textsuperscript{3} which took into account both linear and cubic in $k$ terms in the energy spectrum. Within framework of this theory four characteristic magnetic fields
describe the behavior of interference induced magnetoresistance in the presence of spin relaxation. They are two standard parameters: $B_{tr} = \hbar / (4eD\tau)$ and $B_{\phi} = \hbar / (4eD\tau_\phi)$, where $D$ is the diffusion coefficient, $\tau$ and $\tau_\phi$ are the momentum and phase relaxation time, respectively, and two additional parameters relevant to spin relaxation: $B_{so} = \hbar / (4eD\tau_s)$ and $B_{so}' = \hbar / (4eD\tau_s')$ with $\tau_s = (2\Omega^2\tau_1 + 2\Omega_3^2\tau_3)^{-1}$, and $\tau_s' = (2\Omega^2\tau_1)^{-1}$. Here, $\Omega$ is equal to $\Omega_R$ or $\Omega_1$, and $\tau_1$ and $\tau_3$ are the transport relaxation times introduced as $\tau_i^{-1} = \int (1 - \cos i\theta)W(\theta)d\theta$, where $W(\theta)$ is the probability of the scattering per angle $\theta$ per unit time (note, $\tau_1 = \tau$).

The value of $B_{tr}$ was found in the ordinary way using the results of Hall and conductivity measurements. The other three parameters are in principle free and can be used as the fitting ones. However, our analysis shows that the experimental data for structure 3635 are in excellent agreement with ILP-expression under the condition $B_{so} = B_{so}'$ [see Fig. 2]. The temperature dependences of $\tau_\phi$ and $\tau_s$ for $V_g = 0$ are presented in Fig. 3(a). It is seen that the fitting parameter $\tau_s$ is independent of $T$ that corresponds to the Dyakonov-Perel mechanism of spin relaxation. The temperature dependence of $\tau_\phi$ is close to the $T^{-1}$-law predicted by conventional theory for the temperature dependence of the phase relaxation time when the dephasing is caused by inelasticity of electron-electron interaction. Such a natural behavior of $\tau_s$ and $\tau_\phi$ with temperature allows us to believe that we have experimentally obtained the phase and spin relaxation times.

The fact that the fitting procedure does not fail at $B_{so} = B_{so}'$ means that the main contribution to antilocalization comes from the linear in $k$ term. In order to understand what mechanism, Rashba or Dresselhaus, is responsible for the energy splitting resulting in the spin relaxation, we have performed self-consistent calculations of the electron energy spectrum within framework of $kP$-model.

Let us start with consideration of the Rashba mechanism. It is not so difficult to obtain rather reliable theoretical results in this case because the heterostructure geometry and all the material parameters are known. Figure 3(b) shows the electron density dependences of the energy splitting obtained experimentally as $\Delta = \hbar / \sqrt{2\tau_s}$ together with the results of calculations of $\Omega_R$. It is seen that the theoretical values of the splitting is strongly less than experimental ones in whole electron density range. From the first sight it seems unnatural because the structure 3635 was grown with strong In-gradient within the quantum well. However our analysis shows that the contribution of inclined part of the well (see Fig. 1(a)) to the splitting is compensated by that of the right-side abrupt InGaAs/GaAs interface.
FIG. 3: (a) The temperature dependence of $\tau_{\phi}$ and $\tau_s$ found from the fitting procedure for structure 3635 at $V_g = 0$. (b) The value of $\tau_s$ and energy splitting $\Delta = \hbar/\sqrt{2\tau_s}$ as functions of electron density controlled by the gate voltage for structure 3635. Symbols are the experimental data, dashed line is result of self-consistent calculations for the Rashba spin-orbit splitting $\Omega_R$, solid lines are provided as a guide for the eye.

This effect takes place due to insufficient height of the right-side barrier that results in strong penetration of the wave function into it. Thus, we conclude that not Rashba effect is responsible for the antilocalization in the structure 3635.

To calculate the energy splitting caused by the Dresselhaus effect one needs to know the value of parameter $\gamma$. This parameter is expressed through seven (!) band parameters of the volume material. Not all of them are known with high enough accuracy, therefore, we have obtained the parameter $\gamma$ experimentally. For this purpose we have used the experimental results obtained for the structures Z76 and 3512. For these structures it was impossible to fit satisfactorily the experimental $\sigma$-versus-$B$ curves by ILP-formula under the condition $B_{so} = B_{so}'$. This means that both linear and cubic in $k$ terms contribute to antilocalization in these structures. To simplify the fitting procedure in this case we did not consider the parameters $B_{so}$ and $B_{so}'$ as independent ones. We supposed that they were interrelated via the energy spectrum and scattering anisotropy in accordance with their definition: $B_{so}/B_{so}' = 1 + \Omega_3^2\tau_3/(\Omega^2\tau_1)$, where $\Omega$ stands for $\Omega_1$ or $\Omega_R$. The ratio $\Omega_3/\Omega$ was chosen equal to that found from the calculation of the energy spectrum. The ratio $\tau_3/\tau_1$ was from the range 0.5...0.7 depending on the scattering anisotropy which in its turn
FIG. 4: The values of $\Omega_R$, $\Omega_1$, and $\Omega_3$ as functions of electron density for structures 3512, Z76 (a), and 3635 (b). Circles are the experimental data for $T = 0.45$ K (open symbols) and 1.5 K (solid symbols), lines are the result of self-consistent calculations.

depended on the electron density. The best fit of $\sigma$-versus-$B$ curves has been achieved when $\Omega = \Omega_1$ that points to the fact that the main contribution to the spin relaxation comes from the Dresselhaus effect. The final results of such a data processing for structures Z76 and 3512 are shown in Fig. 4(a) by symbols. Comparing the experimental and calculated electron density dependences of $\Omega_1$ and $\Omega_3$ we have found that the best agreement between theory and experiment is achieved for $\gamma = 18$ eV Å³ (lines in Fig. 4(a)). An overall error in determination of $\gamma$ can be estimated as ±2 eV Å³. Finally we can return to the results obtained for the structure 3635. Figure 4(b) demonstrates satisfactory agreement between experimental data and results calculated with just the same value of $\gamma = 18$ eV Å³.

Comparing Figs. 4(a) and 4(b) one can see that the $\Omega_3$ to $\Omega_1$ ratio is close for both symmetric and asymmetric structures. The reasonable question arises in this connection: why does not the cubic in $k$ splitting contribute to the antilocalization in structure 3635? From our point of view one of possible reason is that the doped layer is more spaced from the quantum well in this structure as compared to the other structures. This results in smoother scattering potential and stronger scattering anisotropy which in its turn determines the relative contribution of cubic and linear terms in antilocalization via $\tau_3$ to $\tau_1$ ratio.
IV. CONCLUSION

We have investigated the antilocalization caused by the spin-orbit interaction in GaAs/In$_x$Ga$_{1-x}$As/GaAs quantum wells with and without gradient of indium content in growth direction. It has been found that the Dresselhaus effect is responsible for antilocalization in both types of the heterostructures. The comparison of experimental data with the results of self-consistent calculations allows us to determine reliably the value of $\gamma$ parameter:

$$\gamma = (18 \pm 2) \text{eVÅ}^3.$$  

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