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Spin Effects in Magnetoresistance Induced in an n-In$_x$Ga$_{1-x}$As/GaAs Double Quantum Well by a Parallel Magnetic Field

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Abstract—Magnetoresistance in n-In$_x$Ga$_{1-x}$As/GaAs ($x \approx 0.18$) heterostructures with double quantum wells (DQWs) was studied in the magnetic field parallel to the DQW layer. Specific features of the magnetoresistance, related to the passing of the tunnel gap edges across the Fermi level, are revealed and studied. Agreement between the calculated and experimental positions of the observed features is obtained when the spin splitting of the energy spectrum is taken into account. Earlier, similar features were observed in the magnetoresistance of n-GaAs/Al$_x$Ga$_{1-x}$As DQW heterostructures, but the spin effects did not manifest themselves.

A system of coupled 2D conducting layers, or a double quantum well (DQW), is an object of interest both because of its possible applications (see, e.g., [1]) and the fundamental physics involved [2]. It attracts attention due to the possible existence of collective correlated interlayer states, which give rise to new electronic phases or lead to a broadening of the existing range of phases known in a separate 2D layer [2, 3]. Furthermore, the recent attention given to studies of spin transport (spintronics) has increased the interest in the spin effects of processes in DQWs, and several experiments indicate the existence of nontrivial effects (see, e.g., [4]). We should note that, all over the world, the vast majority of research into DQWs is performed in a GaAs/Al$_x$Ga$_{1-x}$As heterosystem, because it provides the best quality layers, owing to a minimum lattice mismatch. We have studied the magnetoresistance and Hall effect in a DQW formed in an n-In$_x$Ga$_{1-x}$As/GaAs heterosystem in a magnetic field normal ($B_\perp$) or parallel ($B_\parallel$) to the layers of the structure. In contrast to a GaAs/Al$_x$Ga$_{1-x}$As system, in which the spin splitting of the conduction band of GaAs is very small, the spin effects in the In$_x$Ga$_{1-x}$As/GaAs system may be much more pronounced. This is because the g-factor of electrons in InAs, which is one of the components of the In$_x$Ga$_{1-x}$As solid solution that forms the potential well, is larger than in GaAs by a factor of about 35.

The structures under study consist of two In$_{0.18}$Ga$_{0.82}$As potential wells, 5 nm in width and separated by a thin GaAs barrier, and of adjacent GaAs side barriers, each containing a Si δ-doped layer separated from the nearest In$_{0.18}$Ga$_{0.82}$As layer by an undoped spacer of 19 nm in width. In this study we present the data for two samples, nos. 2981 and 2984, whose parameters are listed in the table: n_s is the total density of the electron gas in two layers; μ, the mobility at low temperatures; Δ_{SAS}, the tunnel gap between the energies of the symmetric and antisymmetric states; and E_F, the Fermi level. The last two quantities, and also the potential profiles of the structures, were obtained using a self-consistent solution of the Schrödinger and Poisson equations in a zero field.

In the magnetic field normal to the structure plane, a clear picture of the quantum Hall effect (Fig. 1) is observed, which corresponds to the complicated structure of DQW levels quantized by the magnetic field. The interest in studies focusing on the magnetic field parallel to the structure plane is related to the fact that it is possible to observe and analyze features in the energy spectrum that are not masked by quantization.

In layers of finite thickness, the effect of the magnetic field parallel to the structure plane $B_\parallel$ consists in the following:

(i) a diamagnetic shift of the quantum-confinement levels E_i so that the spacing between these levels increases;

Table

Sample no.	Barrier width, nm	n_s, 10^{15} m^{-2}	μ, m^2 V^{-1} s^{-1}	Δ_{SAS}, meV	E_F, meV
2981	7	2.05	2.6	7.4	8
2984	3.5	2.34	1.6	23.1	9.5

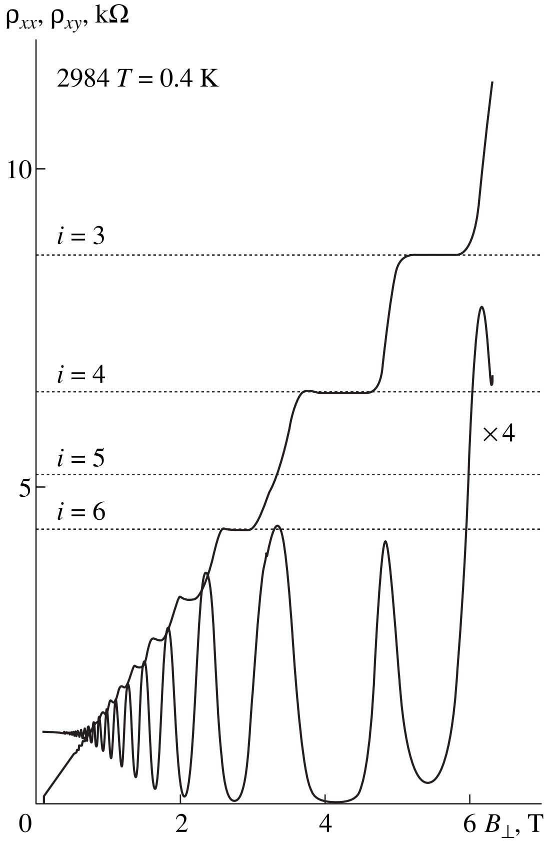

Fig. 1. The quantum Hall effect and magnetoresistance in sample no. 2984.

(ii) a shift of the constant-energy surfaces $E_i(k_\|)$, $k_\| = (k_x, k_y)$ along the k_y direction [5].

The last factor is important in DQWs, because the energy-dispersion surfaces of the two layers $E_i^{1,2}(k_\|)$ are shifted with respect to each other by $\Delta k_{yi} = eB_\| d_i/\hbar$ (Fig. 2), where d_i is the effective spacing between the centers of mass in layers for the *i*th subband [6]. Furthermore, we only discuss the processes related to the evolution of the ground subband, so the index *i* will be omitted. If tunneling between the layers is possible, the level of a separate well in a DQW is split into two levels with symmetric (S) and antisymmetric (AS) wave functions and separated by the tunnel gap Δ_{SAS}. At a relative lateral shift in the *k*-space of $E^{1,2}(k_\|)$ paraboloids in parallel magnetic field, the gap Δ_{SAS} is bound to the line of their intersection (Fig. 2). As a result, a complex surface of constant energy $E(k_\|)$ is formed in the DQW. It consists of an inner surface with the minimum E_m at $k = 0$, which corresponds to the upper edge of Δ_{SAS}, and an outer surface with a saddle point E_s at $k = 0$, corresponding to the lower edge of the gap. As the magnetic field increases and the paraboloids move farther apart in the k_y direction, the gap is shifted upwards.

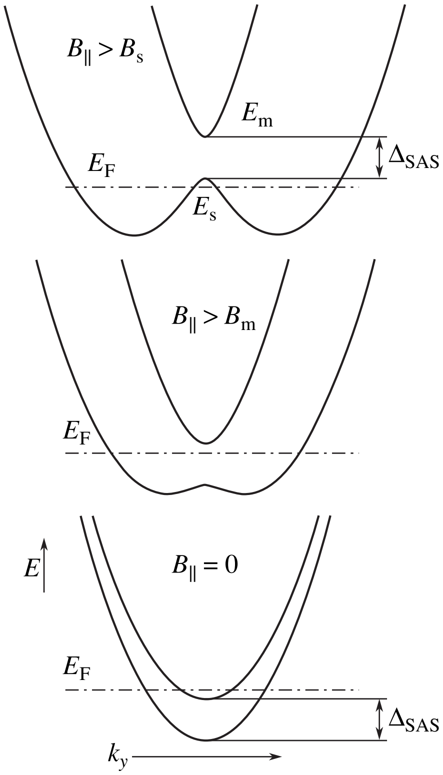

Fig. 2. The evolution of the energy structure of the DQW in the magnetic field $B_\|$ parallel to the structure plane.

As can be seen in the table, initially, in a zero field, the Fermi level E_F in sample no. 2981 lies above the gap Δ_{SAS}. Therefore, in a field B_m the Fermi level will be crossed by the minimum E_m, and after that, in the field $B_s > B_m$, by the saddle point (Fig. 2). As a result, the total density of the states at the Fermi level decreases stepwise at $B_\| > B_m$, and the intersubband transitions will be switched off, which will induce a stepwise decrease or a minimum in the magnetoresistance $\rho(B_\|)$ at $B_\| \approx B_m$. The van Hove singularity in the density of the states is related to the saddle point E_s; this singularity will cause the magnetoresistance maximum in the field $B_\| \approx B_s$. Indeed, in this sample we did observe a minimum and maximum in the magnetoresistance $\rho(B_\|)$ (see Fig. 3). At the same time, in sample no. 2984, which had a barrier two times thinner and, consequently, a significantly wider gap Δ_{SAS}, the Fermi level lay in the gap below the minimum E_m even in a zero field. Therefore, in this case, there is no reason for the formation of a minimum in magnetoresistance at $B_\| \approx B_m$, and only a maximum can exist at $B_\| \approx B_s$, which we did observe in the pulsed magnetic field at about $B_s \approx 30$ T (Fig. 3). Features of this kind were earlier observed in $\rho(B_\|)$, but only in DQWs formed in GaAs/Al$_x$Ga$_{1-x}$As structures [7].

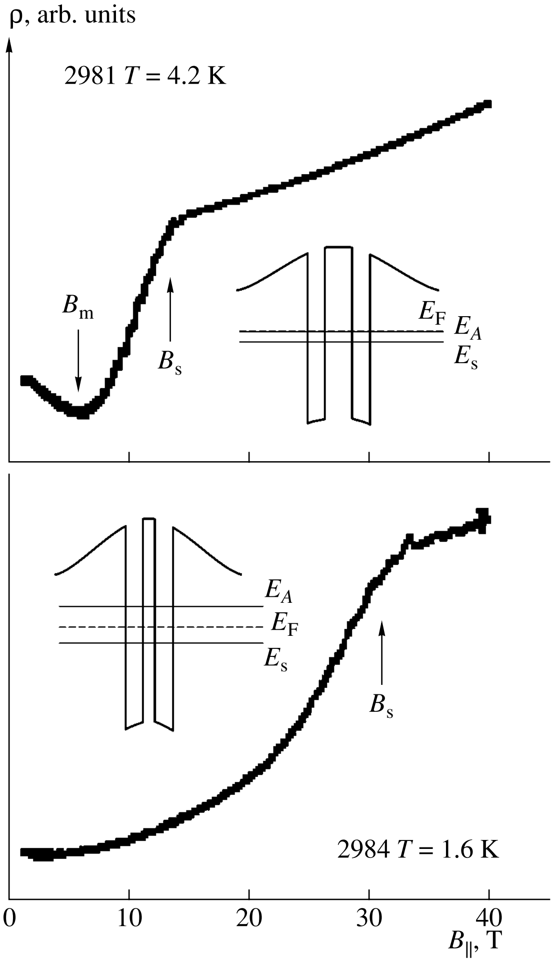

Fig. 3. Resistance $\rho(B_{\parallel})$ vs. the intensity of the magnetic field parallel to the structure plane. Insets: calculated potential profiles and energy levels.

The energy dispersion in the DQW in the parallel field was calculated in terms of a two-level model:

$$E_{1,2} = \frac{\hbar^2(k_x^2 + k_y^2)}{2m} + \frac{H_{ss} + H_{aa}}{2} \pm \frac{1}{2}\sqrt{(H_{ss} - H_{aa})^2 + 4H_{sa}^2}, \quad (1)$$

where

$$H_{ss} = E_s + \frac{m}{2}\omega^2\langle s|z^2|s\rangle,$$

$$H_{aa} = E_a + \frac{m}{2}\omega^2\langle a|z^2|a\rangle,$$

$$H_{sa} = -\hbar\omega k_y\langle s|z|a\rangle,$$

$\omega = eB_{\parallel}/m$; m is the effective electron mass; $|s\rangle$ and $|a\rangle$, the symmetric and antisymmetric wave functions in the DQW; and E_s and E_a, the lower and upper edges of the gap in the zero magnetic field.

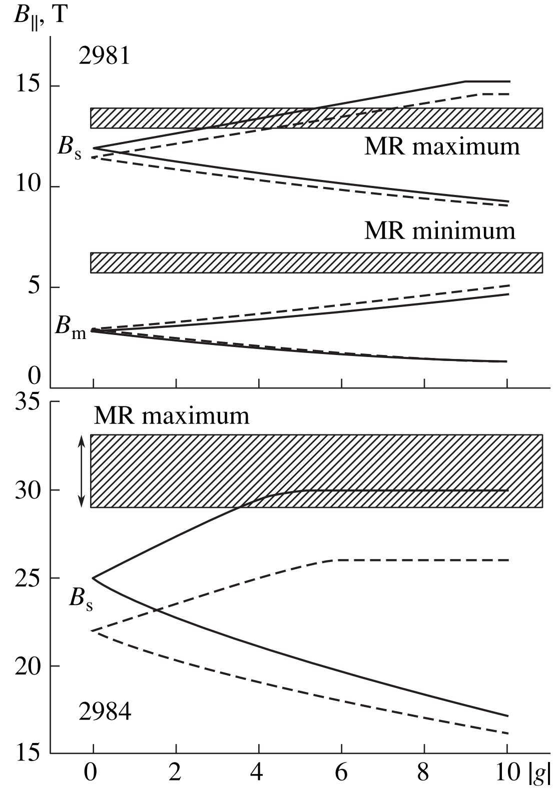

Fig. 4. A comparison of the measured values of $B_{\parallel}$, corresponding to the maximum and minimum of the magnetoresistance (shaded areas) with the values calculated as functions of the g-factor. The dashed lines represent simplified calculations on the assumption $\langle s|z^2|s\rangle = \langle a|z^2|a\rangle = 0$ [6]; and the solid lines, the data of more precise calculations.

The simplest approximation was used in [6], where the assumption $\langle s|z^2|s\rangle = \langle a|z^2|a\rangle = 0$ was employed. In this case, the gap

$$H_{aa} - H_{ss} = E_a - E_s = \Delta_{SAS}$$

does not vary with the magnetic field. This approximation is sufficiently precise to estimate the magnetic field B_s for sample no. 2981, which has a wide barrier, but is too inaccurate in the case of the wide gap in sample no. 2984, which has a thin barrier (Fig. 4). Calculations made without this approximation show that, in fact, the gap increases as the field increases, and becomes, in a field of 30 T, nearly twice as large as in a zero field (Figs. 5a, 5d).

A comparison between the calculated and experimental positions of the features in the magnetoresistance (Fig. 4, $g = 0$) shows a reasonable agreement for the position of the maximum, B_s, for sample no. 2981, but the position of the minimum, B_m, is underestimated in the calculations. Figure 4 shows the results calculated for infinitely narrow levels.

Our calculations of the total density of the states at the Fermi level, DOS(E_F), as function of the magnetic field $B_{\parallel}$ show that the broadening of levels dE leads to a

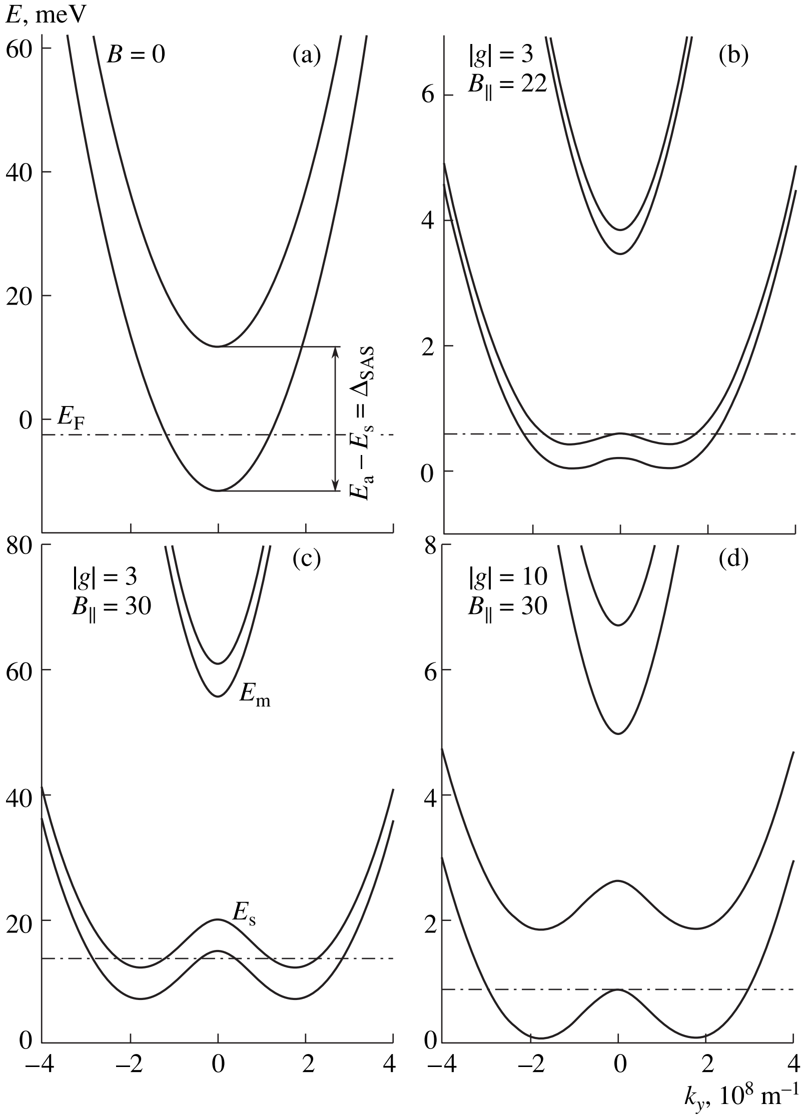

Fig. 5. The energy dispersion in the conduction band along k_y for sample no. 2984, calculated for different values of $B_\parallel$ (in tesla) and the g-factor, denoted in the figure.

considerable shift of the B_m minimum to a higher $B_\parallel$ (Fig. 6a), and the calculated data agree with the experiment. This shift is related to the fact that, in a zero field, the Fermi level lies in the upper subband, in the immediate vicinity of its edge, and is on the verge of departing from it. As the field increases in the range of weak fields, it moves nearly in parallel with the lower spin sublevel. More reliable conclusions follow from an analysis of the magnitude of the field B_s, which is not varied when the levels are broadened.

For sample no. 2984, the calculation of the position of the maximum in $\rho(B_\parallel)$ using the approximate method yields a strongly underestimated magnitude of the field, B_s (see Fig. 4, the point of convergence of dashed lines for sample no. 2984 at $g = 0$). This discrepancy can be noticeably diminished in more precise calculations (see Fig. 4, the point of convergence of solid lines for sample no. 2984 at $g = 0$) but not eliminated. Elimination only becomes possible if the spin splitting of the states is taken into account. In this case, summands $\pm g\mu_B B_\parallel/2$ are introduced into (1), where μ_B is the Bohr magneton (Fig. 4). Then, the calculated value of B_s for the saddle point of the lower spin-split subband agrees with the experiment for a g-factor with $|g| > 3$. The interpolation between InAs and GaAs ($g = -15$ and $g = -0.44$, respectively) yields $g \approx -3$ for $In_{0.18}Ga_{0.82}As$. The spin splitting in our samples is distinctly observed in perpendicular fields (Fig. 1), where it manifests itself even in the field $B_\perp \approx 5$ T as a feature of the quantum Hall effect for the odd integer $i = 3$ at the Hall resistance $\rho_{xy} = h/e^2 i$. The initiation of the state for $i = 5$ in a field of ~3 T can also be seen.

A comparison of Figs. 5b and 5c offers a possible explanation of the fact that the features related to the

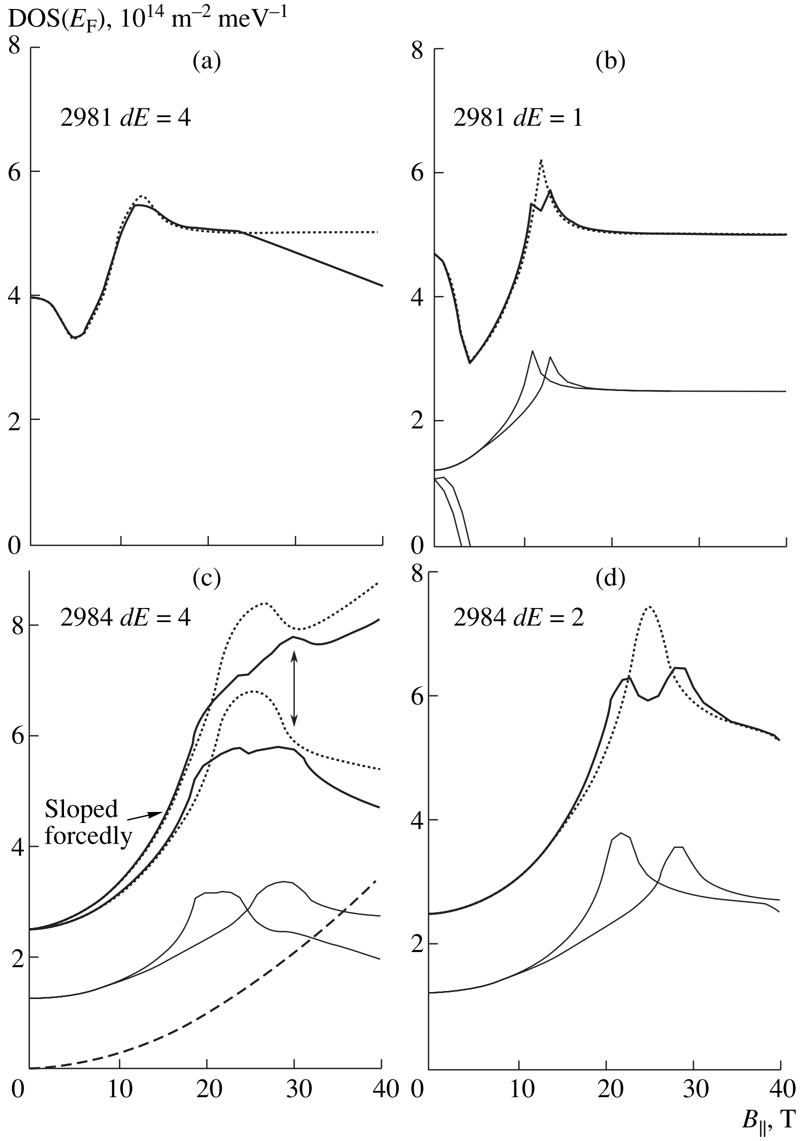

Fig. 6. The density of the states at the Fermi level, DOS(E_F), calculated for (a, b) sample no. 2981 and (c, d) sample no. 2984: $g = 3$ (solid lines) and $g = 0$ (dotted lines). The level broadening dE: (a, c) 4, (b) 1, and (d) 2 meV. Thin solid lines represent the result of calculations for separate subbands; and thick lines, the sum of these. An increasing function (dashed line) is added to reflect the rise in the background component of the magnetoresistance as the field increases (c); the total density of the states that account for this artificial rise is shown by the two upper lines in the figure.

saddle point in the upper of the spin-split subbands are not observed in the $\rho(B_\parallel)$ dependence for sample no. 2984. In the field $B_\parallel = 22$ T, the saddle point is not formed yet, and the corresponding change in the density of the states is masked by features in that density, which are related to side minima of the same subband with close energies. In contrast, at 30 T the saddle points are resolved; i.e., they lie far enough, in terms of energy, from the minima of their subbands. Moreover, as can be seen in Fig. 5c, at $|g| = 3$ the saddle point of the lower subband almost coincides with the minima of the upper subband, which can enhance the total density-of-states peak at the Fermi level in a field of ~30 T.

These arguments are supported, to some extent, by a calculation of the density of the states at the Fermi level, DOS(E_F), as a function of the magnetic field. As can be seen in Fig. 6c, at a certain broadening of the levels, the features in the density of the states in the upper subband are smeared, but the feature related to the saddle point in the lower subband remains discernible (marked with a vertical arrow). However, calculations of only the density of the states fail to provide a complete description of the dependence of the resistance on a magnetic field. The features related to the upper spin sublevel are manifested in the calculated data in the form of a wide shoulder on the $\rho(B_\parallel)$ dependence, in fields below 30 T, which is not the case in the experiment. Furthermore, the calculated total DOS(E_F) decreases as the field increases in the range of high fields (Figs. 6a, 6c), which occurs because the Fermi level passes into the lower spin subband, whereas in the experiment, in contrast, the magnetoresistance increases in both samples.

A strong positive magnetoresistance in single layers in the parallel field was observed in several studies [8, 9], where the spin polarization of the electron gas was suggested as the possible mechanism responsible for this effect. In our experiments, we also observed a spin polarization when the upper spin subband is depleted in the field $B_{||} > B_s$. It is necessary to note, however, that in the mentioned studies, a metal-type behavior of the resistance was observed, and it was assumed that the spin polarization depresses the mechanisms responsible for this metal-type behavior. In contrast, in our samples, the resistance steadily increases as the temperature decreases in the whole range studied, down to $T \approx 0.3$ K. At the same time, in [9], a positive magnetoresistance was observed, also at low densities, in the region of the insulating state. Thus, the reason why the resistance grows as $B_{||}$ increases is not clear yet.

A comparison of Figs. 5c and 5d allows us to understand why the $B_s(|g|)$ dependences (Fig. 4) level off: after the total depletion of the upper spin subband, the Fermi level becomes rigidly fixed within the lower subband.

An estimation of the level broadening from the mobility values gives $dE \approx 1$ meV. The somewhat higher values of dE, which were to be used in our calculations, to fit the experiment, can be justified by the fact that level broadening is defined by the quantum lifetime of electrons (which depends on all the scattering processes). This period can be several times shorter than the transport lifetime determined from the mobility. Figures 6b and 6d show the magnetoresistance behavior that would be expected at a smaller broadening of levels.

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