RESPONSE OF THE TWO-DIMENSIONAL ELECTRON GAS OF AlGaAs/GaAs HETEROSTRUCTURES TO PARALLEL MAGNETIC FIELD

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We study the transport properties of the two-dimensional electron gas in AlGaAs/GaAs heterostructures in parallel to the interface magnetic fields at low temperatures. The magnetoresistance in the metallic phase is found to be positive and weakly anisotropic with respect to the orientation of the in-plane magnetic field and the current through the sample. At low electron densities ($n_e < 5 \times 10^{10} \text{ cm}^{-2}$) the experimental data can be described adequately within spin-related approach while at high $n_e$ the magnetoresistance mechanism changes as inferred from $n_e$-independence of the normalized magnetoresistance.

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Much interest has been aroused recently by the behaviour of two-dimensional (2D) electron systems in a parallel magnetic field. The resistance of a 2D electron gas in Si MOSFETs was found to rise steeply with parallel field $B_\parallel$ saturating to a constant value above a critical magnetic field $B_c$ which depends on electron density [1][2][3]. Such a behaviour of the resistance agrees well with data on the metal-insulator phase diagram for the case of parallel fields of Ref. [1] where the suppression of the metallic phase by $B_\parallel$ was observed. The insensitivity of the effect to the orientation of $B_\parallel$ with respect to the current through the sample [1][2] as well as its isotropy in weak, tilted magnetic fields [4][5] hint at the spin origin of the effect. Recently, an analysis of Shubnikov-de Haas oscillations in tilted magnetic fields has established that the field $B_c$ corresponds to the onset of full spin polarization of the electron system [6][7]. The influence of $B_\parallel$ on the resistance of the 2D hole gas in GaAs heterostructures was found to be basically similar to the case of Si MOSFETs [8] with two noteworthy distinctions: (i) above $B_c$, the resistance keeps on increasing less steeply with no sign of saturation [9]; and (ii) the magnetoresistance is strongly anisotropic depending upon the relative orientation of the in-plane magnetic field and the current [10].

The early version of the theory of the spin origin of parallel field effects exploits scaling arguments for calculating the temperature-dependent magnetoresistance in the metallic phase in the low field limit [11]. An alternative concept has been expressed recently based on the fact that the 2D electron screening of a random potential depends on the relative population of spin-up and spin-down subbands [12]; at zero temperature the magnetoresistance is expected to be positive for relatively low electron densities in the metallic phase and is determined by the spin polarization of 2D electrons which is defined as the ratio of the Zeeman splitting and the Fermi energy $\xi = g \mu_B B / 2 E_F$. Above the critical field $B_c$ corresponding to the condition $\xi = 1$, the resistance $R(B_\parallel)$ should saturate at the level of the four-fold zero-field resistance. While the spin-related approach [12] allows the interpretation of the resistance rise with $B_\parallel$ in Si MOSFETs, the strongly anisotropic magnetoresistance observed on the 2D holes in GaAs heterostructures is likely to point to a contribution of the orbital effects of Ref. [13] where it was shown that for a 2D system with finite thickness the form of the Fermi surface changes in a parallel magnetic field.

In a number of recent publications, the occurrence of a zero-magnetic-field metal-insulator transition in Si MOSFETs and for the 2D holes in GaAs as well as the origin of the effects observed in parallel magnetic fields have been attributed to strong particle-particle interaction as characterised by the Wigner-Seitz radius $r_s$ (see, e.g., Ref. [14]). Oppositely, for the 2D electrons in GaAs heterostructures the values of $r_s$ are almost an order of magnitude lower, particularly, because of the small effective mass, which is traditionally expressed in terms of weak electron-electron interaction in GaAs. Nevertheless, for the 2D electrons in both GaAs [1] and Si MOSFETs [15], similar metal-insulator phase diagrams were obtained in normal magnetic fields including a zero field [16] and so the parameter $r_s$ is not crucial in this case. The obvious consequence of the small effective electron mass in GaAs is that much higher values of the critical magnetic field $B_c$ are expected [17].

Here, we investigate the influence of parallel magnetic field on the resistance in the metallic phase of the 2D electron system in GaAs heterostructures. We observe a positive magnetoresistance which is weakly anisotropic with respect to the orientation of the in-plane magnetic field and the current through the sample. This finding is similar to results reported for the 2D electrons in Si MOSFETs and the 2D holes in GaAs heterostructures and enables us to split the parallel magnetic field effect from the problem of the interaction-induced metal-insulator transition. The spin mechanism allows the description of the experimental data at low electron densities but fails in the opposite limit in which the normalized magnetoresistance is found to be independent of $n_e$. 
Our devices are 170 μm wide conventional Hall bars based on an AlGaAs/GaAs heterostructure that is grown on a (100) GaAs substrate and contains a high mobility 2D electron gas. The density \( n_s \) of the 2D electrons is controlled using a gate on the front surface of the device. The behaviour of the low-temperature mobility \( \mu \) in the studied range of electron densities is depicted in the top inset to Fig. 1. For our samples the conductivity remains in the metallic regime down to \( n_s \approx 2 \times 10^{10} \) cm\(^{-2} \). The sample is placed in the mixing chamber of a dilution refrigerator with a base temperature of 30 mK. The measurements are performed using a standard four-terminal lock-in technique at a frequency of 10 Hz in magnetic fields up to 14 T. The ac current \( I \) through the device does not exceed 1 nA. Two samples made from the same wafer have been investigated; the results obtained on these are practically identical.

To change the sample position in the mixing chamber we warm the sample up, rotate it at room temperature, and cool it down again. The alignment uncertainty of the sample plane with the magnetic field is kept within 0.3°. We use small misalignments ≤ 2° to observe quantum oscillations caused by a perpendicular component of the magnetic field and evaluate the \( g \) factor from the oscillation beating pattern [18], see the bottom inset to Fig. 1. The electron density as a function of gate voltage is determined from quantum oscillations in normal magnetic fields. We have checked that the gate voltage dependence of the resistance at \( B = 0 \) is well reproducible in different coolings of the sample with an accuracy of insignificant threshold shifts. In parallel magnetic fields, this dependence is used for determining the threshold voltage.

A typical experimental trace of the resistivity \( \rho(B_{||}) \) is shown in Fig. 1 for the parallel and perpendicular orientations of \( B_{||} \) relative to the current \( I \). The magnetoresistance is close to a parabolic dependence, being smaller in the parallel configuration. As is evident from Fig. 1, the magnetoresistance anisotropy is not strong, approximately a factor of 1.2. The observed resistance rise reaches a factor of three at the lowest \( n_s \) and the highest magnetic fields, displaying no tendency of saturation. The temperature dependence of the resistance is practically absent in the interval between 30 and 600 mK. We emphasize that in the presence of a small normal component of the magnetic field as caused by misalignment the dependence \( \rho(B_{||}) \) is drastically distorted. As seen in the bottom inset to Fig. 1 the effect is dramatic even for small misalignments ∼ 1°.

By scaling the \( B_{||} \)-axis we make the normalized resistivity traces \( \rho(B_{||})/\rho(0) \) at different electron densities collapse onto a single curve simultaneously for each of the two field directions (Fig. 2). At low \( n_s \) the scaling factor \( B_c \) is found to enhance approximately linearly with electron density (top inset to Fig. 2). At higher \( n_s > 5 \times 10^{10} \) cm\(^{-2} \) the normalized resistivity \( \rho(B_{||})/\rho(0) \) becomes independent of \( n_s \) (Fig. 2) such that the scaling parameter \( B_c \) saturates.

Thus, we observe a strong rise of the resistance with

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**FIG. 1.** Dependence of the sample resistivity on parallel magnetic field for \( B_{||} \perp I \) at \( n_s = 7.4 \times 10^{10} \) cm\(^{-2} \) (solid line) and \( B_{||} \parallel I \) at \( n_s = 7.5 \times 10^{10} \) cm\(^{-2} \) (dashed line). The top inset shows the mobility as a function of electron density. Bottom inset: behaviour of the normalized resistivity with magnetic field in the perpendicular field to current orientation for the in-plane \( B \) (solid line) and the field tilted by 1.2° relative to the sample plane (dashed line).

**FIG. 2.** Scaling the magnetic field dependence of the normalized resistivity of the sample at low \( n_s \). Also shown by a dashed line is a fit using the theory of Ref. [2]. The scaling parameter \( B_c \) as a function of electron density is displayed in the top inset. The bottom inset shows the resistivity as a function of filling factor \( \nu \) for two tilt angles of the magnetic field.
parallel magnetic field in the metallic regime in the 2D electron system with \( r_s \) spanning between 2 and 3.5, the range in which \( \rho(0) \) changes by more than an order of magnitude. The effect is weakly anisotropic relative to the orientation of \( B_\parallel \) and \( I \) and is qualitatively similar to that found in 2D systems with strong particle-particle interaction, \( r_s \gtrsim 10 \). In contrast to the conclusion of Refs. [3,4], we do not suppose that the observed dependence \( \rho(B_\parallel) \) is due to electron-electron interaction because in our case the \( r_s \) values are considerably smaller. Particularly, the parallel field effect can be considered regardless of the interaction-induced metal-insulator transition.

Two different approaches that predict the change of \( \rho \) with \( B_\parallel \) in a 2D system with weak electron-electron interaction have been formulated [12,13]. To compare our data with the theoretical predictions we reason as follows. The absence of strong anisotropy of the observed magnetoresistance allows one to presume the dominance of spin effects as discussed in the theory of Ref. [2]. This theory demands, in particular, identifying \( B_\parallel/B_c \) with the spin polarization \( \xi \), i.e., \( B_c = 2E_F/g\mu_B \) (where \( E_F = \pi\hbar^2 n_s/m \) and \( m \) is the effective mass). The dashed line in Fig. 3 is drawn in accordance with the theory; its best fit to the data as shown in the figure yields the normalizing condition for the parameter \( B_c \). Although the consistency between experiment and theory is fairly good, there are problems with such a description of the data. Firstly, the accessible magnetic fields are not high enough to reach the expected saturation of the resistance. Secondly, the scaling parameter \( B_c \) becomes independent of electron density at \( n_s > 5 \times 10^{10} \text{ cm}^{-2} \). Thirdly, the so-defined critical field \( B_c(n_s) \) corresponds to the \( g \) factor \( g \approx 2.2 \) which is much larger than its bulk GaAs value of \( g = 0.44 \). In fact, at low electron densities the \( g \) factor is expected to be enhanced due to electron-electron interaction as discussed in the Fermi liquid model (see, e.g., Ref. [19]). An independent check of the beating pattern of Shubnikov-de Hass oscillations in slightly nonparallel magnetic fields gives a crude estimate \( 0.7 < g < 1.4 \), which is still small compared to the parallel field data [20]. The noticeably smaller values of \( B_c \) obtained in the experiment as well as the saturation of \( B_c \) at high electron densities are in contrast to the behaviour of the critical field \( B_c \) found in Refs. [12,13] and cause us to invoke alternative mechanisms of the parallel field magnetoresistance. The most likely candidate is an orbital effect caused by the finite thickness of the 2D electron system [13]. Its contribution would naturally explain the observed magnetoresistance anisotropy and weaker dependence \( B_c(n_s) \). Nevertheless, we believe that at low electron densities the spin-related concept [12] describes the magnetoresistance adequately because with decreasing \( n_s \) the orbital effect (or any other mechanism that yields \( n_s \)-independent scaling parameter \( B_c \)) is overpowered by the spin effect as will be discussed below.

In a 2D electron system with finite thickness the parallel magnetic field deforms the Fermi surface so that the effective mass in the normal to \( B_\parallel \) direction increases leading to a positive magnetoresistance, whereas the one in the parallel direction remains unchanged and so the resistance [13]. An example of the deformed Fermi surface as calculated in triangular potential approximation is displayed in the inset to Fig. 4 for different magnitudes of \( B_\parallel \). With increasing magnetic field the Fermi surface broadens in the \( k_\perp \) direction and narrows in the \( k_\parallel \) direction to keep its area constant, shifting as a whole along \( k_\parallel \). For lower \( n_s \), the distortion of the Fermi sur-
face is stronger and so the magnetoresistance is larger, see Fig. 4. Although the model [13] yields the correct order of magnitude of the magnetoresistance for the perpendicular field to current orientation (cf. Figs. 3 and 4), it cannot describe the relatively weak magnetoresistance anisotropy as well as $\rho(B_{||})/\rho(0)$ at different $n_s$. At the same time, the theoretical magnetoresistance changes with electron density not so strongly as the one predicted by the spin-related model [12]. Apparently, this is the condition for switching the dominant magnetoresistance mechanism: at low $n_s$ the spin mechanism of the magnetoresistance prevails while at high $n_s$ the orbital effect is likely to become dominant.

In our opinion, the approach of Ref. [13] should be completed by including a change of the relaxation time in a parallel magnetic field. The following aspects seem important: (i) the increase of the Fermi surface perimeter leads to shortening the relaxation time; (ii) the increase of the density of states at the Fermi energy results in a better screening by the 2D system and, hence, increasing the relaxation time; and (iii) the anisotropy of screening. Their account should cause, at least, a reduction of the anisotropy of the theoretical magnetoresistance.

In summary, we have investigated the transport properties of the 2D electrons in AlGaAs/GaAs heterostructures in parallel to the interface magnetic fields at low temperatures. It has been found that the magnetoresistance in the metallic phase is positive and weakly anisotropic with respect to the orientation of the in-plane magnetic field and the current through the sample. This is basically similar to data obtained for the 2D electrons in Si MOSFETs and the 2D holes in GaAs heterostructures, although the electron-electron interaction in GaAs is considerably weaker. Therefore, our experiment splits the parallel magnetic field effect from the problem of the interaction-induced metal-insulator transition. At low electron densities the spin-related model is capable of describing the experimental results while at high $n_s$ neither approach can explain $n_s$-independence of the normalized magnetoresistance.

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