Hole-hole interaction in a strained In$_x$Ga$_{1-x}$As two dimensional system

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The interaction correction to the conductivity of 2D hole gas in strained GaAs/In$_x$Ga$_{1-x}$As/GaAs quantum well structures was studied. It is shown that the Zeeman splitting, spin relaxation and ballistic contribution should be taken into account for reliable determination of the Fermi-liquid constant $F_0^x$. The proper consideration of these effects allows us to describe both the temperature and magnetic field dependences of the conductivity and find the value of $F_0^x$.

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I. INTRODUCTION

The transport properties of two dimensional (2D) systems reveal the intriguing features. One of the features is a metallic-like temperature dependence of the resistivity ($\partial \rho / \partial T > 0$) at low temperature in some kind of 2D systems, e.g., in n-Si MOSFET and 2D hole gas in Al$_x$Ga$_{1-x}$As/GaAs and Ge$_{1-x}$Si$_x$/Ge structures (see Refs. 1 and 2 and references therein). As a rule such a behavior is observed in the structures with large value of the gas parameter $r_s = \sqrt{2/(a_B k_F)}$, where $a_B$ and $k_F$ are the Bohr radius and Fermi quasimomentum, respectively, which characterizes the electron-electron ($e-e$) or hole-hole ($h-h$) interaction strength.

Up to now there is not conventional opinion whether the metallic-like temperature dependence of the conductivity attests on quantum phase transition or it results from the interaction correction to the conductivity. For low $r_s$-values and within the diffusion regime ($T \tau \ll 1$, where $\tau$ is the transport relaxation time and $h/k_B = 1$), the interaction correction is, as a rule, negative and increases in absolute value with the lowering temperature. However, for the intermediate ($T \tau \approx 1$) and ballistic ($T \tau \gg 1$) regimes this correction can change sign leading to the metallic behavior of the resistivity ($\partial \rho / \partial T > 0$). Such effect crucially depends on the value of the Fermi-liquid constant $F_0^x$ (see Figs. 7 and 8 in Ref. 3), therefore the experimental determination of the interaction correction to the conductivity and the value of $F_0^x$ is a central point of numerous papers during the last few years.

Unlike the case of structures with the electron 2D gas there are some difficulties in extraction of the interaction correction to the conductivity in p-type structures with complex valence band, especially, for the low hole density. First of all, the large value of perpendicular $g$-factor (which responsible for the Zeeman splitting in magnetic field perpendicular to the structure plane) leads to an additional temperature dependence and appearance of magnetic field dependence of the interaction correction $\delta \sigma_{xx}^e$ even in the diffusion regime. Besides, for the high mobility 2D hole gas, the parameter $T \tau$ is usually greater than unity for all available temperatures, the ballistic contribution is important and, therefore, the interaction correction contributes not only to $\sigma_{xx}$, but to $\sigma_{xy}$ as well. Strong anisotropy of $g$-factor (we mean the strongly different Zeeman splitting in in-plane and perpendicular magnetic field) makes it difficult to determine the reliable value of $F_0^x$ from in-plane magnetoresistance experiments. Most likely just these facts lead to a very...
large scatter in the $F_0^\sigma$-values determined for the 2D hole gas in different papers as illustrated by Fig. 11. Moreover the the value of $F_0^\sigma$ determined from the different effects in the same structures, namely, from the temperature dependence of the conductivity at $B = 0$ and from the temperature dependence of $\rho_{xx}$, occurs significantly different.\footnote{12}

For the first sight, it may appear that the scatter in $F_0^\sigma$ is not so large. However, it should be pointed out that the $F_0^\sigma$-sensitivity of the $h$-$h$ interaction correction is very strong. So, a variation of $F_0^\sigma$ within the scatter range leads to the strong variation in the value of interaction correction so that even the sign of the correction becomes different in the diffusion regime. This illustrates by the inset in Fig. 11, where the changing of this correction at tenfold temperature variation as a function of $F_0^\sigma$ is plotted.

From our point of view for the reliable determination of $F_0^\sigma$ and eucletion of the role of $e$-$e$ ($h$-$h$) interaction in the forming of the metallic-like temperature dependence of the conductivity it is necessary to study it thoroughly starting from the conditions, under which the theories are attested, i.e., at low enough $r_s$-value and in the circumstances, where the ballistic contribution is not dominant.

In the present paper we study the $h$-$h$ interaction correction to the conductivity for the low-mobility, high-density $[p = (3.9 - 7.2) \times 10^{11} \text{ cm}^{-2}]$ $p$-type quantum well heterostructures with $r_s \simeq 1.5 - 2.3$ within the temperature range from 0.4 to 4.4 K, when the parameter $T\tau$ lies within the interval from 0.02 to 0.8 that captures the diffusion region.

II. THEORETICAL BACKGROUND

Let us begin with the diffusion regime, $T\tau \ll 1$. For $B = 0$, the $e$-$e$ ($h$-$h$) correction to the conductivity gives the logarithmic contribution to the conductivity

$$\frac{\delta\sigma^{ee}(T)}{G_0} = \left[1 + 3\left(1 - \frac{\ln(1 + F_0^\sigma)}{F_0^\sigma}\right)\right] \ln T\tau, \quad (1)$$

where $G_0 = e^2/(2\pi^2\hbar) \approx 1.23 \times 10^{-5} \text{ cm}^{-1}$, the first term in square brackets is the exchange or the Fock contribution while the second one is the Hartree contribution (the triplet channel). In most cases the value in the square brackets is positive and at $T\tau \ll 1$ the interaction correction is localizing and leads to the logarithmic decrease of the conductivity with the temperature decrease.

The specific feature of the interaction correction in this regime is the fact that in magnetic field it contributes to $\sigma_{xx}$ and does not to $\sigma_{xy}$.\footnote{17}

$$\delta\sigma_{xx}^{ee} = \delta\sigma^{ee}(T) \quad (2)$$

$$\delta\sigma_{xy}^{ee} = 0. \quad (3)$$

As shown in Ref. 14, Eqs. \((2)\) and \((3)\) remain to be valid in a classically strong magnetic field. The absence of the interaction contribution to $\sigma_{xy}$ leads to the parabolic magnetic field dependence of $\rho_{xx}$ at $\delta\sigma_{xx}^{ee}(T) \ll \sigma_{xx}$:

$$\rho_{xx}(B, T) \approx \frac{1}{\sigma_0} - \frac{1}{\sigma_0^2} (1 - \mu^2 B^2) \delta\sigma_{xx}^{ee}(T). \quad (4)$$

The following peculiarity of the interaction induced parabolic negative magnetoresistance is evident. Despite the fact that the curvature of the parabola $\rho_{xx}(B)$ is temperature dependent, there is the point at $B = \mu^{-1}$, in which all the parabolas relating to different temperatures should cross each other.

Note, we will use the exact relationship between resistivity and conductivity tensor components

$$\rho_{xx} = \frac{\sigma_{xx}}{\sigma_{xx}^2 + \sigma_{xy}^2}. \quad (5)$$

because Eq. \((1)\) markedly deviates from Eq. \((5)\) already at $\delta\sigma_{xx}^{ee}(\mu B)^2 \gtrsim (0.05 - 0.1)\sigma_{xx}$.

Up to now we neglected the Zeeman splitting. Taking it into account results in the appearance of the magnetic field dependence of $\delta\sigma_{xx}^{ee}$ at $E_z/T \gtrsim 1$ where $E_z = g\mu_B B$. This is because that the magnetic field suppresses two components of the triplet channel while the Fock contribution and one component of the triplet channel remain unchanged. As a result, the multiplier 3 in Eq. \((1)\) should be replaced by 1 in high magnetic field, $E_z/T \gg 1$. The general expressions for the magnetic field dependence of the interaction correction were obtained in Ref. 15 for the weak interaction and in Ref. 16 for the arbitrary one. However, they are too complicated and it is not convenient to use them in practice. Much simpler expression, which well approximates these formulae has been proposed by I. V. Gornyi.\footnote{17}

$$\frac{\delta\sigma_{xx}^{ee}}{G_0} = \ln T\tau + \left(1 - \frac{(1 + F_0^\sigma)}{F_0^\sigma}\right) \times \left[\ln T\tau + 2 \ln \sqrt{1 + \left(E_z/T\right)^2}\right]. \quad (6)$$

It is clear that the sensitivity of $\delta\sigma_{xx}$ to the magnetic field strength via the Zeeman splitting results in the more complicated $B$-dependence of the magnetoresistance as compared with the parabolic one, Eq. \((5)\). Nevertheless, the magnetoresistance curve retains the parabolic-like shape in classically strong magnetic field.

Note, namely the fact that the $e$-$e$ ($h$-$h$) interaction in the diffusion regime contributes only to $\sigma_{xx}$ gives a possibility to extract reliably this contribution from the experimental data.

Let us now consider the more general case when both the diffusion and ballistic contributions are of importance. In the absence of magnetic field the interaction correction read:\footnote{17}

$$\frac{\delta\sigma_{ee}^{ee}}{G_0} = 2\pi T\tau \left[1 - \frac{3}{8} f(T\tau) + \frac{3\tilde{F}_0^\sigma}{1 + F_0^\sigma}\right].$$
In explicit form the functions $f(T\tau)$ and $t(T\tau, \tilde{F}_0^\sigma)$ are given in Ref. 13. The relationship between $\tilde{F}_0^\sigma$ and $F_0^\sigma$ can be found from the simultaneous solution of the equations written out in page 6 of Ref. 3. However, it is much simpler to use the following approximate formula, which accuracy is better than 2 % when $F_0^\sigma = -(0.02 \ldots 0.5)$:

$$\tilde{F}_0^\sigma \simeq F_0^\sigma \left[ 1.25 \left(F_0^\sigma \right)^{0.69} + 0.223 \right].$$

(8)

In the presence of magnetic filed, the situation is more complicated as compared with the purely diffusion regime, because the e-e (h-h) interaction gives a contribution not only to $\sigma_{xx}$ but to $\sigma_{xy}$ as well. Theory for the ballistic and intermediate regime, when the strong inequality $T\tau \ll 1$ is not fulfilled, is developed for classically low perpendicular magnetic field in Ref. 13. The ballistic regime for the high magnetic field was considered in two papers, Refs. 15 and 13. However, all the analytical results in Ref. 15 are presented for the limiting cases: $\omega_c \tau \gg 1$, $E_z/T \gg 1$. Under our experimental conditions these inequalities are not fulfilled. Therefore we will use the results obtained in Ref. 13 where the influence of Zeeman splitting was studied for the in-plane magnetic field orientation. According to this paper and Ref. 3 one can write the following expression for the interaction correction in the presence of parallel magnetic field

$$\delta\sigma_{ee}^\parallel(B, T) = \delta\sigma_{ee}^\parallel(0, T) + \Delta\sigma_\parallel(B, T),$$

(9)

where the first term $\delta\sigma_{ee}^\parallel(0, T)$ is given by Eq. 10 and the second one is

$$\Delta\sigma_\parallel(B, T) = 2\pi G_0 \left[ \frac{2\tilde{F}_0^\sigma}{1 + \tilde{F}_0^\sigma} T \tau K_b \left( \frac{E_z}{2T}, \tilde{F}_0^\sigma \right) \right] + K_d \left( \frac{E_z}{2\pi T}, F_0^\sigma \right) + m(\ldots).$$

(10)

Here, the functions $K_b(x, \tilde{F}_0^\sigma)$ and $K_d(x, F_0^\sigma)$ given by Eqs. (12) and (15) from Ref. 13. The function $m(\ldots)$ describes the crossover between diffusion and ballistic regimes and only slightly modifies the sum of the first two terms in Eq. (10). The first term in Eq. (10) describes the ballistic contribution and the second one does the diffusion contribution.

To adapt these results for the analysis of data obtained in the presence of perpendicular magnetic field we will take into account the following two well known facts relating to the limiting cases. In the purely diffusion regime, the e-e (h-h) interaction contributes to $\sigma_{xx}$ and does not to $\sigma_{xy}$ as seen from Eqs. 2 and 3. In the ballistic regime, the role of the interaction reduces to the renormalization of the transport relaxation time $\tau$. In this basis, we suppose that the conductivity components for the arbitrary temperature and magnetic field values with consideration for the Zeeman splitting are

$$\sigma_{xx} = \frac{e^2 n}{m} \frac{\tau'}{1 + (\omega_c \tau')^2} + 2\pi G_0 K_d \left( \frac{E_z}{2\pi T}, \tilde{F}_0^\sigma \right) + \delta\sigma_{ee}(T),$$

$$\sigma_{xy} = \frac{e^2 n}{m} \frac{\omega_c \tau'^2}{1 + (\omega_c \tau')^2}.$$ (11)

(12)

where $\tau'$ is the momentum relaxation time modified by the ballistic contribution as

$$\tau' = \tau \left[ 1 + \frac{T}{E_F} \left[ 1 - \frac{3}{8} f(T\tau) \right] + \frac{3\tilde{F}_0^\sigma}{1 + \tilde{F}_0^\sigma} \left( 1 - \frac{3}{8} t(T\tau, \tilde{F}_0^\sigma) \right) + \frac{2\tilde{F}_0^\sigma}{1 + \tilde{F}_0^\sigma} K_b \left( \frac{E_z}{2\pi T}, \tilde{F}_0^\sigma \right) \right].$$

(13)

The magnetic and temperature dependences of $\rho_{xx}$ are obtained in ordinary way with the help of Eq. 13.

We realize that this way is not rigorous. However, to the best of our knowledge there is not exact solution accounting for all the peculiarities mentioned above.

To conclude this section, the interaction correction has to reveal itself in the different aspects: (i) it should influences the temperature dependence of the conductivity in the absence of the magnetic field; (ii) it specifically changes the temperature and magnetic field dependences of the conductivity tensor component $\sigma_{xx}$ and $\sigma_{xy}$ in the presence of magnetic field. It is clear that only in the case when all the mentioned above dependences are well described in the framework of a common model one can consider the result as conclusive and the value of the parameter $F_0^\sigma$, which determines the value of interaction correction, can be considered as found reliably.

### III. EXPERIMENT

We have studied the interaction correction in the heterostructures GaAs/In$_x$Ga$_{1-x}$As/GaAs grown by metalorganic vapor phase epitaxy on semi-insulator GaAs substrate. The lattice mismatch between In$_x$Ga$_{1-x}$As and GaAs results in biaxial compression of the quantum well. Two types of heterostructures were studied. The structures of the first type, 3855 and 3857, consist of a 250 nm-thick undoped GaAs buffer layer, carbon δ-layer, a 7 nm spacer of undoped GaAs, a 10 nm In$_0.2$Ga$_{0.8}$As well, a 7 nm spacer of undoped GaAs, a carbon δ-layer and 200 nm cap layer of undoped GaAs. The structure of the second type, 3951, was analogous, the only difference was
the wider spacer, 15 nm, and as sequence the higher momentum relaxation time. The samples were mesa etched into standard Hall bars and then an 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 change the hole density and mobility (transport relaxation time) in the quantum well (see Table I).

For the quantitative interpretation of the experimental results one needs to know the effective mass and $g$-factor. The hole effective mass in the structures investigated has been experimentally determined from the temperature dependence of the amplitude of the Shubnikov-de Haaas oscillations. It is equal to $(0.160 \pm 0.005) m_0$ and does not depend on the hole density. This value differs appreciably from the theoretical one, which can be easily estimated. It can be done with the help of the Luttinger-Kohn Hamiltonian\textsuperscript{20} which includes the terms responsible for the strain.\textsuperscript{23} Since the Fermi energy, $E_F \simeq 5 - 10$ meV, in our case is much less than the strain induced splitting of the valence band, $2|S| \simeq (80 - 90) \text{ meV}\textsuperscript{22}$ the in-plane hole effective mass should be equal to $m_h = (\gamma_1 + \gamma_2)^{-1} m_0$, where $\gamma_i, i = 1, 2,$ are the Luttinger parameters. If one supposes that the Luttinger parameters of the solid solution In$_x$Ga$_{1-x}$As are $\gamma_i(x) = \left(x/\gamma_i^{\text{InAs}} + (1-x)/\gamma_i^{\text{GaAs}}\right)^{-1}$, and uses the values of $\gamma_i^{\text{InAs}}$ and $\gamma_i^{\text{GaAs}}$ from Ref. 23 we obtain $m_h/m_0 = (\gamma_1 + \gamma_2)^{-1} \simeq 0.1$ for In$_{0.2}$Ga$_{0.8}$As, which is significantly less than the experimental value. Such a discrepancy was already reported\textsuperscript{24,25} and, to the best of our knowledge, has not an adequate explanation up to now.

As for the $g$-factor, its experimental value is unknown for holes in strained In$_x$Ga$_{1-x}$As quantum wells. Theoretical value of $g$-factor for the states with small energy, $\epsilon \ll 2|S|$, is $g = 6 \kappa$, where $\kappa$ is the Luttinger parameter responsible for the spin splitting. The use of interpolation formula $\kappa(x) = \left(x/\kappa^{\text{InAs}} + (1-x)/\kappa^{\text{GaAs}}\right)^{-1}$ gives $g \simeq 8.5$. Remembering the difference between experimental and theoretical values of $m_h$ we suppose that the ratio of the cyclotron to Zeeman energies should in reality be the same as predicted theoretically. Thus, we will use $g = 5$ for In$_{0.2}$Ga$_{0.8}$As.

Now we are in position to consider the experimental data. The role of $h$-$h$ interaction in the structures investigated is evident from the magnetic field dependences of $\rho_{xx}$, $\rho_{yy}$ (a), and $\rho_{xy}$ (b) measured at different temperatures for structure 3857 at $V_g = 2.65$ V.

![FIG. 2: The magnetic field dependences of $\rho_{xx}$, $\rho_{yy}$ (a), and $\rho_{xy}$ (b) measured at different temperatures for structure 3857 at $V_g = 2.65$ V.](image)

Let us firstly analyze the experimental data for $B = 0$. The temperature dependence of the conductivity for two heterostructures with different electron density is presented in Fig. 3. A strong deviation of the temperature dependence of $\sigma$ from the logarithmic law is a result of the spin relaxation, which affects the logarithmic behavior of the interference correction. An importance of the spin relaxation is evident from the low-field magnetoresistance curves (see inset in Fig. 3a). The results of detailed studies of this correction for the structures investigated were published in Ref. 22. It has been shown that the Hikami-Larkin-Nagaoka expression\textsuperscript{21} well describes the interference correction that allows us to find the gate-voltage and temperature dependences of the phase and spin relaxation times and subtract the interference correction from the experimental $\sigma$-vs-$T$ dependence. The results are presented in Fig. 3 by open symbols. Surprisingly, after such subtraction the conductivity becomes temperature independent practically. Thus, we observe the discrepancy: the $h$-$h$ interaction correction to the conductivity reveals itself in the magnetoresistance curves (see Fig. 2), but does not in the temperature dependence of the conductivity at $B = 0$ (see Fig. 4). One of the reasons of this discrepancy can be the ballistic contribution, which radically affects the temperature dependence of the conductivity at $B = 0$ for some $F_{0}^\gamma$ values as mentioned in Section I.

To estimate the value of $F_{0}^\gamma$ let us analyze the mag-

**TABLE I: The parameters of structures investigated**

| Structure | $V_g$ (V) | $p$ ($10^{11}$ cm$^{-2}$) | $\tau$ ($10^{-13}$ s) |
|-----------|-----------|----------------|------------------|
| 3855      | $-0.75$   | 6.3            | 5.8              |
| 3857      | 1.50      | 7.2            | 5.9              |
|           | 2.00      | 6.7            | 5.4              |
|           | 2.65      | 5.6            | 3.7              |
| 3951      | 0.00      | 5.0            | 13               |
|           | 0.75      | 4.6            | 11               |
|           | 1.25      | 3.9            | 9                |
netoresistance at lowest temperature where the ballistic contribution is rather small. In Fig. 4(a) we present the experimental \( \rho_{xx} \)-vs-\( B \) dependences at lowest temperature together with the calculated ones with the different values of \( F_0^\sigma \). To make the result of the comparison more clear we present in Fig. 4(b) the differences between experimental and calculated curves. The range of the low magnetic field \( B < 10B_{\tau\tau} \approx 1.3 \) T, where the interference correction is significant is cut off. On can see that the best agreement occurs at \( F_0^\sigma = -0.35 \). Note, the calculated \( \rho_{xx} \)-vs-\( B \) curve does not depend strongly on the specific value of \( F_0^\sigma \). Besides, the strong dependence on \( g \)-factor value is absent as well. The low sensitivity to \( g \)-factor is a sequence of the fact that the main contribution to \( \delta \sigma_{xx} \) within actual range of the magnetic field comes from the Fock term [which is independent of \( F_0^\sigma \) and \( g \)-factor as evident from Eq. (3)], because the Hartree contribution is strongly suppressed at \( B > 2 \) T. The written is illustrated by the inset in Fig. 4.

Thus taking into account the possible uncertainty in the value of \( g \)-factor we estimate the accuracy in the determination of \( F_0^\sigma \) as \( \pm 0.05 \). The close value of \( F_0^\sigma \) was obtained by this way for other gate voltages and other structures under the condition \( T\tau \lesssim 0.05 \).

It may appear from Eq. (10) that one can determine the values of \( g \)-factor and \( F_0^\sigma \) from the analysis of magnetoresistance measured in in-plane magnetic field. However such method could be useful being applied to a system with isotropic \( g \)-factor. For our case of 2D hole gas in strained structures, the \( g \)-factor is extremely anisotropic. In particular, the in-plane \( g \)-factor should be equal to zero for the states with the energy significantly less than the strain induced splitting. Really, the in-plane magnetoresistance \( \rho_{||}(B) \) is practically absent as Fig. 2(a) illustrates.

Let us now elucidate the role of the ballistic contribution at \( B = 0 \) for \( F_0^\sigma = -(0.3 . . . 0.4) \) within actual \( T\tau \)-range. To do this we have calculated from Eq. (7) the temperature dependences of the difference \( \Delta \sigma(T) = \delta \sigma_{ee}(T) - \delta \sigma_{ee}(0.5 \) K) (Fig. 5). One can see that the behavior of \( \Delta \sigma(T) \) strongly depends on value of \( F_0^\sigma \) for actual range of \( F_0^\sigma \) and \( T\tau \). In addition, the slope of the curves calculated with taking into account ballistic contribution and without that are strongly different even at \( T\tau < 0.1 \). This means that the ballistic contribution is important for actual values of \( F_0^\sigma \) and \( T\tau \), in particular the total interaction correction becomes temperature independent up to \( T\tau = 0.4 \) at \( F_0^\sigma = -0.37 \). In the same figure we present the experimental data obtained for the different gate voltages and different structures. Comparing them with the theoretical curves we have found the values of \( F_0^\sigma \) and plotted them in the inset in Fig. 5 as a function of \( r_s \). One can see that the experimental data
The $T\tau$ dependence of the interaction correction. Solid lines are the dependences of $\Delta\sigma(T) = \delta\sigma_{ee}(T) - \delta\sigma_{ee}(0.5K)$ calculated from Eq. (11) with the different values of $F_0^\sigma$. The dashed lines are the diffusion contribution with the same values of the parameter $F_0^\sigma$. The symbols are the experimental data after the subtraction of the interference correction for the structure 3857, $V_g = 2.65$ V ($\Delta$), 2 V ($o$), and 1.5 V ($|$), and for the structure 3951, $V_g = 0$ V (□). The inset shows the values of $F_0^\sigma$ found from the analysis of the dependences $\sigma(T)$ (△) and $\rho_{xx}(B)$ (○) and plotted against the gas parameter $r_x$. Solid line is the result of Ref. 6.

We believe that a more detailed analysis of the data in the magnetic field when the ballistics is important oversteps the accuracy of the approximations made above. Besides, one has to perceive that 2D hole gas is not suitable object for the experimental study of the interaction correction in the ballistic regime. The reason is the large value of the Zeeman splitting and high spin relaxation rate, which strongly modify both the temperature and magnetic field dependences of the conductivity. From our point of view, the interaction correction in intermediate regime, where there are not firm theoretical predictions, should be studied firstly for the simpler situation which is realized in 2D electron gas. Such studies are in progress.

To demonstrate how our values of $F_0^\sigma$ relate to the results of the previous papers we plot them in Fig. 6. One can see that the scatter of our experimental points is not larger and they lie closely to theoretical curve. In our opinion the large scatter of the earlier data is a sequence of the improper consideration of the Zeeman splitting, the spin relaxation and the ballistic contribution, which play an important role in 2D hole gas.
IV. CONCLUSION

We have studied the interaction correction to the conductivity of 2D hole gas in strained GaAs/In$_{0.7}$Ga$_{0.3}$As/GaAs quantum well structures. We have shown that for the reliable determination of the value of the Fermi-liquid constant $F_\sigma^r$ from the magnetic field dependences of conductivity in the diffusion regime one has to take into account the Zeeman splitting, while for its determination from the temperature dependence of the conductivity in zero magnetic field the spin relaxation has to be properly accounted. We have found that for $r_s = 1.5 - 2.3$ the value of $F_\sigma^r$ is equal to $-0.35 \pm 0.05$. It has been shown that for this $F_\sigma^r$-value the ballistic contribution is important starting from $T \tau \approx 0.05$.

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1. A. K. Savchenko, Y. Y. Proskuryakov, S. S. Safonov, L. Li, M. Pepper, M. Y. Simmons, D. A. Ritchie, E. H. Linfield, and Z. D. Kvon, Physica E 22, 218 (2004).
2. V. M. Pudalov, M. E. Gershenson, H. Kojima To be published in: Chapter 19, Proceedings of the EURESCO conference "Fundamental Problems of Mesoscopic Physics", Granada, 2003
3. G. Zala, B. N. Narozhny, and I. L. Aleiner, Phys. Rev. B 64, 214204 (2001).
4. H. Noh, M. P. Lilly, D. C. Tsui, J. A. Simmons, E. H. Hwang, S. D. Sarma, L. N. Pfeiffer, and K. W. West, Phys. Rev. B 68, 165308 (2003).
5. C. J. Emleus, T. E. Whall, D. W. Smith, N. L. Mattey, R. A. Kubiak, E. H. C. Parker, and M. J. Kearney, Phys. Rev. B 47, 10016 (1993).
6. M. Simmons, A. Hamilton, M. Pepper, E. Linfield, P. Rose, and D. Ritchie, Phys. Rev. Lett. 84, 2489 (2000).
7. L. Li, Y. Y. Proskuryakov, A. K. Savchenko, E. H. Linfield, and D. A. Ritchie, Phys. Rev. Lett. 90, 076802 (2003).
8. Y. G. Arapov, V. N. Neverov, G. I. Harus, N. G. Shelushinina, M. V. Yakumin, O. A. Kuznetsov, A. de Visser, and L. Ponomarenko, cond-mat/0404355.
9. Y. G. Arapov, G. I. Harus, O. A. Kuznetsov, V. N. Neverov, and N. G. Shelushinina, Fiz. Tekn. Poluprov. 33, 1073 (1999).
10. P. T. Coleridge, A. S. Sachrajda, and P. Zawadzki, Phys. Rev. B 65, 125328 (2002).
11. V. Senz, T. and Ilm, T. Heinzel, K. Ensslin, G. Dehlinger, D. Grutzmacher, and U. Gennser, Phys. Rev. Lett. 85, 4357 (2000).
12. C. E. Yasin, T. L. Sobey, A. P. Micolich, A. R. Hamilton, M. Y. Simmons, L. N. Pfeiffer, K. W. West, E. H. Linfield, M. Pepper, and D. A. Ritchie, cond-mat/0403411.
13. B. L. Altshuler and A. G. Aronov, in Electron-Electron Interaction in Disordered Systems, Edited by A. L. Efros and M. Pollak (North Holland, Amsterdam, 1985).
14. A. Houghton, J. R. Senna, and S. C. Ying, Phys. Rev. B 25, 2196 (1982).
15. A. M. Finkelstein, Zh. Eksp. Teor. Fiz. 84, 168 (1983) [Sov. Phys. JETP 57, 97 (1983)].
16. C. Castellani, C. Di Castro, P. A. Lee, Phys. Rev. B 57, R9381 (1998).
17. I. V. Gornyi, unpublished.
18. I. V. Gornyi and A. D. Mirlin, Phys. Rev. B 69, 045313 (2004).
19. G. Zala, B. N. Narozhny, and I. L. Aleiner, Phys. Rev. B 65, 020201 (2002).
20. J. M. Luttinger and W. Kohn, Phys. Rev. 97, 869 (1955).
21. G. E. Bir and G. L. Pikus, Symmetry and strain induced effects in semiconductors (Chichester:Wiley, 1974).
22. G. M. Minkov, A. A. Sherstobitov, A. V. Germanenko, O. E. R. V. A. Larionova, and B. N. Zvonkov, Phys. Rev. B 71, ?? (2005).
23. I. Vurgaftman, J. R. Meyer, and L. R. Ram-Mohan, J. of Appl. Phys. 89, 5815 (2001).
24. D. Lancefield, A. R. Adams, A. T. Menev, A. Knap, E. Litwin-Staszewska, C. Skierbiszewski, and J. L. Robert, J. Phys. Chem. Solids 56, 469 (1995).
25. Shawn-Yu Lin, H. P. Wei, D. C. Tsui, and J. F. Klem, Appl. Phys. Lett. 67, 2170 (1995).
26. The magnetoresistance decreases in magnitude with increasing temperature and practically disappears at $T \approx 30$ K (not shown in Fig. 2). It points to the fact that the classical mechanisms which should lead to the temperature independent negative magnetoresistance do not reveal themselves in our case.
27. E.M. Baskin, L.N. Magarill, and M.V. Entin, Zh. Eksp. Teor. Fiz. 75, 723 (1978) [Sov. Phys. JETP 48, 365 (1978)].
28. A. V. Bobylev, F. A. Maao, A. Hansen, and E. H. Hauge, Phys. Rev. Lett 75, 197 (1995).
29. A. Dmitriev, M. Dyakonov, and R. Jullien, Phys. Rev. B 64, 233231 (2001).
30. A. D. Mirlin, D. G. Polyakov, F. Evers, and P. Wölfle, Phys. Rev. Lett 87, 126805 (2001).
31. S. Hikami, A. I. Larkin, and Y. Nagaoka, Progress of Theoretical Physics 63, 707 (1980).