Pis'ma v ZhETF, vol.67, iss.2, pp.101 - 106

EFFECT OF HOLE-HOLE SCATTERING ON CONDUCTIVITY OF TWO-COMPONENT 2D HOLE GAS IN GaAs/(AlGa)As HETEROSTRUCTURES

*S.S.Murzin, S.I.Dorozhkin, G.Landwehr+, A.C.Gossard**

Institute of Solid State Physics
142432 Chernogolovka, Moscow District, Russia

+Physikalisches Institut der Universität Würzburg
D-97074 Am Hubland, Würzburg, Germany

** University of California*
CA 93106, Santa Barbara, USA

Submitted 23 August 1997

The temperature dependences of both zero-magnetic-field resistivity ρ and magnetoresistance of 2D hole gas in GaAs/(AlGa)As heterostructures have been investigated in the temperature range of 0.4 – 4.2 K. When the temperature T is increased (i) the resistivity ρ grows with the decreasing derivative $d\rho/dT$ and (ii) the positive magnetoresistance diminishes from about 40% at $T = 0.4$ K to about 1% at $T = 4.2$ K. The results have been explained in terms of the temperature dependent mutual scattering of the holes accompanied by the momentum transfer between two different spin-split subbands.

PACS: 72.20.-i, 73.40.Kp

For many years a positive magnetoresistance of up to 40% has been observed in high-mobility 2D hole gas of GaAs/(AlGa)As heterostructures at low temperatures in weak magnetic fields [1 – 7]. First this magnetoresistance was associated with two-carrier conduction [3]. It is known there are two groups of holes with different spectra and mobilities in 2D hole systems of GaAs/(AlGa)As heterostructures. These two groups are formed from the heavy hole band due to the lifting of the spin degeneracy caused by the spin-orbit interaction in the absence of inversion symmetry [8 – 10]. In such a system, a positive magnetoresistance should be observed [11] in the case of both the elastic scattering of holes by impurities and the inelastic scattering by phonons (even with presence of inter-group scattering [12]).

However, in the experiments [2, 4, 7] the magnetoresistance was found to be strongly temperature dependent even at relatively low temperatures, when the electron-phonon scattering is unessential. The magnetoresistance decreases with the temperature so that at $T = 4.2$ K it almost vanishes [2, 7]. Therefore, there were doubts whether the effect is due to two-carrier conduction [4, 6], and new ideas were put forward. In Ref. [2, 4] it was noted that a qualitatively similar effect can be caused by weak localization in a system with strong spin-orbit coupling [13]. However, the weak localization effects are too small to account for large magnetoresistance in highly-conductive heterostructures [2]. The authors of Ref. [6] hypothesized that the magnetoresistance could originate from quantum corrections due to hole-hole interaction in disordered systems at large value of inverse screening length q_s as compared to the hole wave numbers at the Fermi level k_F. It can be shown that the magnetoresistance in this case is also small. The authors of Ref. [7] assumed that the magnetoresistance should be suppressed if the thermal energy k_BT (k_B

is Boltzmann constant) is much larger than the energy separation between the two bands at the wave vector of the smaller Fermi circle Δ_F. However, our calculations show that this factor alone can not suppress the magnetoresistance, but only leads to some canges in its value. Moreover, a drastic decreases in the magnetoresistance is observed when $k_B T \ll \Delta_F$. This factor alone obviously contradicts the idea of the authors of Ref. [7]. Thus there is no satisfactory explanation of the strong temperature dependence of the magnetoresistance of 2D highly-mobility hole gas in GaAs/(AlGa)As heterostructures.

In this paper we propose a new idea, capable of explaining this phenomenon. It is mutual scattering of holes belonging to different groups. By comparing equations derived with both all available data and our detailed study of temperature dependence of the zero-magnetic-field resistance and the magnetoresistance we demonstrate that this effect gives reasonable explanation of the results. It is important that the temperature dependence of the mutual scattering was found to be proportional to T^2 which supports the basic idea.

1.Effect of hole-hole scattering. The positive magnetoresistance in a system with two groups of carriers is caused by the difference between their drift velocities $\mathbf{u}_i$ in an electric field. Intense mutual scattering of carriers should equalize the velocities leading to a vanishing magnetoresistance. The equations introducing the mutual scattering into the transport problem were derived earlier [15 – 18] for the case when the inter-group scattering is absent. Here we use these equations to calculate the zero-magnetic-field resistance and magnetoresistance for the case of carriers with like charges and different mobilities. Although they should not describe the magnetoresistance very accurately we hope that they describe rather well the main features of the phenomenon. The equation of motion in electric field $\mathbf{E}$ and magnetic field $\mathbf{H}$ for particles of group 1, taking into account the collisions with particles of group 2, has the form [16, 17]

$$m_1 \mathbf{u}_1/\tau_1 + \eta n_2(\mathbf{u}_1 - \mathbf{u}_2) = e\mathbf{E} + (e/c)(\mathbf{u}_1 \times \mathbf{H}). \tag{1}$$

A similar equation can be written for the particles of group 2. Here m_i are the effective masses, τ_i are the momentum relaxation times for each group, and η is the mutual friction coefficient

$$\eta = \frac{m_1 m_2}{m_1 n_1 + m_2 n_2}\,\frac{1}{\tau_{e-e}}. \tag{2}$$

Since the relaxation time τ_{e-e} of the relative drift velocity $\mathbf{u}_1 - \mathbf{u}_2$ due to the mutual scattering of carriers is proportional to T^{-2} [21] (see also Appendix), η can be written as

$$\eta = \alpha T^2. \tag{3}$$

By solving the system of equations for $\mathbf{u}_i$ and substituting these velocities into the expression for the current density $\mathbf{j} = n_1 e\mathbf{u}_1 + n_2 e\mathbf{u}_2$, we find the conductivities σ_{xx} and σ_{xy}:

$$\sigma_{xx} = \frac{[nw(He/c)^2 + (\eta n w + w_1 w_2)(\eta n^2 + n_1 w_2 + n_2 w_1)]e^2}{(He/c)^4 + [n^2\eta^2 + 2\eta(n_1 w_2 + n_2 w_1) + w_1^2 + w_2^2](He/c)^2 + (\eta n w + w_1 w_2)^2}, \tag{4}$$

$$\sigma_{xy} = \frac{n(He/c)^2 + (\eta^2 n^3 + 2\eta n(n_1 w_2 + n_2 w_1) + (n_1 w_2^2 + n_2 w_1^2))}{(He/c)^4 + [n^2\eta^2 + 2\eta(n_1 w_2 + n_2 w_1) + w_1^2 + w_2^2](He/c)^2 + (\eta n w + w_1 w_2)^2}\,\frac{e^3}{c}H. \tag{5}$$

Here $w_i = m_i/\tau_i = e/\mu_i$, $n = n_1 + n_2$, $w = (w_1 n_1 + w_2 n_2)/n$. The longitudinal and Hall resistivities are equal to $\rho_{xx} = \sigma_{xx}/(\sigma_{xx}^2 + \sigma_{xy}^2)$, $\rho_{xy} = \sigma_{xy}/(\sigma_{xx}^2 + \sigma_{xy}^2)$. At low temperatures, when $\tau_{e-e} \gg \tau_i$ ($n\eta \ll w$), the conductivity is the sum of the conductivities of each group. In this case our equation for the magnetoresistance coincides with the equation given in Ref. [11]. The magnetoresistance is positive and saturates at high magnetic fields $\mu_i H/c \gg 1$. At high temperatures, when $\tau_{e-e} \ll \tau_i$, the longitudinal resistivity ρ_{xx} and Hall resistivity ρ_{xy} are equal to $\rho_{xx} = 1/ne\mu$, $\rho_{xy} = H/nec$. Here $\mu = e/w$ is the average mobility. In this case, the magnetoresistance is absent and the zero-magnetic-field resistivity ρ does not change with temperature if μ_i are temperature independent. In the intermediate range $\tau_{e-e} \sim \tau_i$ the temperature dependence of the resistance exists only at weak magnetic field $\mu_i H/c \leq 1$. The resistivity ρ_{xx} increases with the temperature and saturates at high temperatures. The difference $\rho(T \to \infty) - \rho(T = 0)$ is equal to the difference $\rho_{xx}(H \to \infty, T = 0) - \rho(T = 0)$.

2. Experiment. The two samples used in experiment were prepared by molecular-beam epitaxy. Sample 1 consisted of a GaAs (100) substrate overgrown with the following layers: undoped GaAs (0.2 μm), a GaAs(20Å)/$Al_{0.26}Ga_{0.74}As$(20Å) periodic structure (20 periods), undoped GaAs (1 μm), undoped $Al_{0.26}Ga_{0.74}As$ (250 Å), $Al_{0.26}Ga_{0.74}As$ doped with Be to $\sim 2.7 \cdot 10^{18}$ cm^{-3} (300 Å), and undoped GaAs (50 Å). Sample 2 differed from sample 1 by the content of Al in $Al_xGa_{1-x}As$ layers ($x = 0.3$), by the thickness of a doped AlGaAs layer which was equal to 200 Å and by a cap layer which consisted of 150 Å of undoped $Al_{0.3}Ga_{0.7}As$ and 100 Å of undoped GaAs.

The densities n_1 and n_2 for the two different groups of holes were determined from the Shubnikov – de Haas oscillations at a low temperature and are listed in Table. This procedure is similar to the one used in Ref. [1, 3]. In fields $H < 1$ T the period of oscillations is determined by the density n_1 of holes with lower mass and density. Above 2 T the period is determined by the total hole density n. For samples 1 and 2 the total densities are $3.23 \cdot 10^{11}$ and $3.43 \cdot 10^{11}$ cm^{-2}, the average mobilities μ at $T = 4.2$ K are $7.4 \cdot 10^4$ and $9.3 \cdot 10^4$ cm^2/V·s, respectively.

Sample	n_1, cm^{-2}	n_2, cm^{-2}	$\mu_{1,0}$, cm^2/V·s	$\mu_{2,0}$, cm^2/V·s	α, g·cm^2/s·K^2	β, 1/K
1	$1.14 \cdot 10^{11}$	$2.09 \cdot 10^{11}$	$22 \cdot 10^4$	$5.4 \cdot 10^4$	$3.7 \cdot 10^{-29}$	0
2	$1.27 \cdot 10^{11}$	$2.16 \cdot 10^{11}$	$24.7 \cdot 10^4$	$7.5 \cdot 10^4$	$2.85 \cdot 10^{-29}$	—
2	$1.27 \cdot 10^{11}$	$2.16 \cdot 10^{11}$	$24.6 \cdot 10^4$	$7.7 \cdot 10^4$	$2.54 \cdot 10^{-29}$	0.02

The temperature dependence of resistivity at $H = 0$ is shown in Fig.1. Both samples show the qualitatively similar behavior. The resistivity increases with the temperature by about 40% with the largest derivative $d\rho/dT$ at low temperatures. Up to $T \approx 3$ K the derivative $d\rho/dT$ decreases and then starts to increase slightly. The magnetoresistance at different temperatures is shown in Fig.2 and 3. The main effect, common for both samples, is a positive temperature dependent magnetoresistance with a tendency to saturation at high magnetic fields. The magnetoresistance strongly decreases when the temperature increases from 0.4 up to 4.2 K.

3. Discussion. The hole-hole scattering explains both the strong decrease of magnetoresistance at high temperatures and the temperature dependence of the zero-magnetic-field resistivity with decreasing $d\rho/dT$ observed at $T < 3$ K. The quantum corrections due to weak localization [13] and hole-hole interaction [14] in our samples should be smaller than 1%. The large value of $\Delta/k_B \approx 10$ K [8, 10] contradicts the explanation given in Ref. [7].

We fitted the experimental data by Eqs.(3) – (5) by varying three unknown parameters, namely, temperature independent mobilities $\mu_{1,0} = e/w_1$, $\mu_{2,0} = e/w_2$ and α, trying to

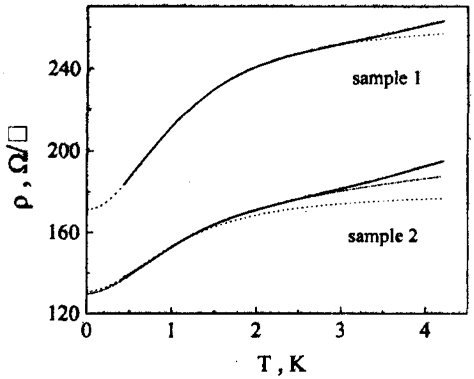

Fig.1 Resistivity at zero magnetic field versus temperature. Solid lines are experimental curves, dotted and dot-dashed lines show theoretical fits with temperature independent and temperature dependent mobilities of holes, respectively

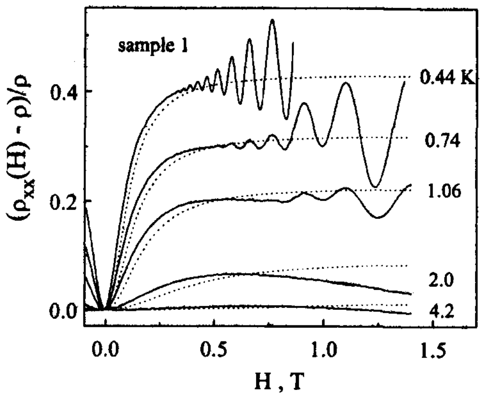

Fig.2. Magnetoresistance $(\rho_{xx} - \rho)/\rho$ of sample 1 at different temperatures in a magnetic field perpendicular to the sample plane. The solid lines are experimental curves, the dotted lines represent the results of fitting

reach the best accuracy at low temperatures. The results of the fitting are shown in Figs.1–3. The chosen values of parameters are listed in Table. The fitting curves describe well the main features of experimental data.

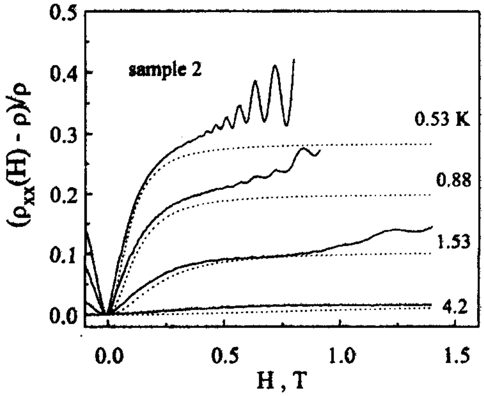

Fig.3. Magnetoresistance $(\rho_{xx} - \rho)/\rho$ of sample 2 at different temperatures. The solid lines are experimental curves, the dotted lines represent the results of fitting

There are several effects which were not taken into account by our simple model. These are inter-group scattering (for the case of elastic scattering this effect was considered by [12]) and anisotropy of the hole Fermi surface. While for elastic scattering by remote impurities (separated by the spacer from a two-dimensional system) the former effect can be suppressed it definitely exists for the hole-hole scattering. These effects can be responsible for some discrepancies between the experimental and the theoretical magnetoresistance curves. The temperature dependence of zero-magnetic-field resistivity should be much less sensitive to these factors. The differences between the fitting and the experimental curves observed in Fig.1 at high temperatures can be explained by the temperature dependence of mobilities μ_i due to electron-phonon scattering and to finite value of k_BT/E_F (E_F is the Fermi energy, $E_F/k_B \approx 20$ K). The biggest correction caused by the latter effect is linear in k_BT/E_F because of the temperature dependence of screening [22]:

$$\mu_i^{-1} = \mu_{i,0}^{-1}(1 + \beta_i T). \tag{6}$$

This effect is important only for scattering with momentum transfer close to $2\hbar k_{F,i}$ ($k_{F,i}$ are the hole wave numbers at the Fermi level) and, therefore, is strongly dependent on the presence of the corresponding harmonics in a particular scattering potential. It can be very different for different samples even with similar structures. The fitting of the data with temperature dependent mobilities given by Eq.(6), where we take $\beta = \beta_1 = \beta_2$, yields considerably better results for sample 2 (see Fig.1). The results for sample 1 were not changed (for this sample β was found to be close to zero). New fitting parameters for sample 2 are also listed in Table. The calculated magnetoresistance curves changed only slightly after taking into account the corrections to μ_i and therefore we do not present new curves. The coefficients β have reasonable values smaller than $k_B/E_F \approx 0.05$ K^{-1}. It is worth noting that at $T = 4.2$ K the differences between experimental and new fitting curves in Fig.1, which we ascribe to the electron-phonon scattering, are approximately equal for both samples.

In order to verify whether η is proportional to T^2 we tried to fit the temperature dependence of the resistivity taking $\eta = \alpha T^p$ with $p = 1.5$ and 2.5 in the temperature range of 0.4-3 K. In both cases the agreement with the experiment was noticeably worse in comparison with the case of $p = 2$.

There are neither experimental nor theoretical data on η, α or τ_{e-e} in 2D two-component electron (hole) gas. In Ref. [21], where the dependence $\tau_{e-e} \propto T^2$ was derived, the factor at T^2 was not calculated. In order to understand whether the values of α obtained from the fitting are reasonable or not, we have calculated τ_{e-e} and η for a simple model, following the approach of Ref. [18]. This model neglects the anisotropy of the real energy spectrum, and assumes the absence of hole transitions from one subband to the other. Although these conditions are not fulfilled in our system, we believe that the calculated value has the correct order of magnitude. Under the condition $q_s = e^2(m_1 + m_2)/\kappa_0\hbar^2 \gg k_{iF}$ (in GaAs/(AlGa)As heterostructures with $n = 3 \cdot 10^{11}$ cm^{-2} $q_s/\max(k_{iF}) \approx 10$)

$$\eta = \frac{8}{3\hbar^3}\left(\frac{m_1 m_2}{m_1 + m_2}\right)^2 \frac{1}{n_1 n_2} \ln\frac{\sqrt{n_1} + \sqrt{n_2}}{\sqrt{n_1} - \sqrt{n_2}} (k_B T)^2. \tag{7}$$

For the case of effective masses $m_1 = 0.2m_e$ and $m_2 = 0.8m_e$ calculated in Ref. [8, 10] we have obtained $\alpha \approx 7 \cdot 10^{-29}$ g·cm^2/s·K^2, for our samples, which is in reasonable agreement with the experimental values.

We have checked that results on the temperature dependent magnetoresistance available in the literature for p-channels in GaAs/AlGaAs heterostructures are consistent with our explanation. Unfortunately the detailed comparison is not possible because, to the best of our knowledge, the only experimental data where the temperature range was large enough to demonstrate strong variation of the magnetoresistance is given by Fig.4 of Ref. [7]. But in this paper only total hole density $n = 2.08 \cdot 10^{11}$ cm^{-2} is presented. Nevertheless we can approximately determine coefficient $\alpha \approx 1 \cdot 10^{-28}$ g·cm^2/s·K^2 for this data because it is not very sensitive to the n_1/n_2 ratio. The data presented in Fig.5 of the same paper for low-mobility sample in temperature range 0.3-1.3 K show only weak temperature dependence of magnetoresistance which implies that τ_{e-e} is much less than elastic scattering time and gives no chance to determine α. The estimation of α is possible for the data presented in Fig.2 of Ref. [4] ($n = 3.8 \cdot 10^{11}$ cm^{-2}, $n_1 = 1.01 \cdot 10^{11}$ cm^{-2}), though the variation of the magnetoresistance there is not large there. This estimation gives $\alpha \approx 1 \cdot 10^{-29}$ g·cm^2/s·K^2. The variation of α with hole density is consistent with the expected dependence (see Eq.A8) at least qualitatively.

In conclusion, we have shown that the temperature dependence of both the zero-magnetic-field resistance and the magnetoresistance of 2D hole gas in GaAs/(AlGa)As heterostructures is governed by the hole-hole scattering at low temperatures. Similar effects can exist in other high-mobility semiconductors systems which contain several groups of carriers with different mobilities.

We acknowledge useful discussion with V. T. Dolgopolov and D. V. Shovkun. This work has been supported by Russian State Programme "Nanostructures" (grant 1-085/4) and by Deutsche Forschungsgemeinshaft.

---

1. H.L.Stormer, Z.Schlesinger, A.Chang et al., Phys. Rev. Lett. **51**, 126 (1983).
2. E.E.Mendez, W.I.Wang, L.L.Chang, and L.Esaki, Phys. Rev. B **30**, 1087 (1984).
3. J.P.Eisenstein, H.L.Stormer, V.Narayanamurti et al., Phys. Rev. Lett. **53**, 2579 (1984).
4. E.E.Mendez, Surf. Scince **170**, 561 (1986).
5. Y.Iye, E.E.Mendez, W.I.Wang, and L.Esaki, Phys. Rev. B **33**, 5854 (1986).
6. Zhou Haiping, Zheng Houzhi, Yang Fuhua et al., Chin. Phys. **10**, 223 (1990).
7. M.Henini, P.A.Crump, P.J.Rodgers et al., J. Crystal Growth **150**, 446 (1995).
8. U.Ekenberg and M.Altarelli, Phys. Rev. B **30**, 3369 (1984).
9. D.A.Broido and L.J.Sham, Phys. Rev. B **31**, 888 (1985).
10. T.Ando, J.Phys. Soc. Jpn. **54**, 1528 (1985).
11. J.M.Ziman, *Principles of the theory of solids*, Cambridge University Press, 1972.
12. E.Zaremba, Phys. Rev. B **42**, 14143 (1992).
13. S.Hikami, A.I.Larkin, and Y.Nagaoka, Progr. Theor. Phys. **63**, 707 (1980).
14. P.A.Lee and T.V.Ramakrishman, Rev. Modern Phys. **57**, 287 (1985).
15. C.A.Kukkonen and P.F.Maldaldague, Phys. Rev. Lett. **37**, 782 (1976).
16. V.F.Gantmakher and Y.B.Levinson, Zh. Eksp. Teor. Fiz. **74**, 261 (1978).
17. V.F.Gantmakher and Y.B.Levinson, *Carrier scattering in metals and semiconductors*, in Modern problems in condensed matter sciences, Vol.**19**, Eds. V.M.Agranovich and A.A.Maradudin, North-Holland, 1987.
18. J.Appel and A.W.Overhauser, Phys. Rev. B **18**, 758 (1978).
19. A.N.Friedman, Phys. Rev. **159**, 553 (1967).
20. A.H.Thompson, Phys. Rev. Lett. **35**, 1786 (1975).
21. C.S.Ting, A.K.Ganguly, and W.Y.Lai, Phys. Rev. B **24**, 3371 (1981).
22. A.Gold, V.T.Dolgopolov, J. Phys. C **18**, L463 (1985); Phys. Rev. B **33**, 1076 (1986).
23. F.Stern, Phys. Rev. Lett. **18**, 546 (1967).