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Large positive quasi-classical magnetoresistance in high mobility 2D electron gas: interplay of short- and long-range disorder

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Abstract

We observed a giant positive quasi-classical magnetoresistance (MR) of high mobility 2D electron gas in AlGaAs/GaAs heterostructure. The MR is non-saturating and increases with the magnetic field as $\rho_{xx} \sim B^{\alpha}$ ($\alpha = 0.9$–1.2). In antidot lattice a non-monotonic behavior is observed. We show that the MR in both cases is well described by the recently advanced theory by Polyakov et al. (Phys. Rev. B 64 (2001) 205306) where non-saturating positive MR and non-monotonic MR in antidot lattice is predicted as the consequence of concurrent existence of short- and long-range scattering.

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Keywords: Two-dimensional electron gas; Quasi-classics; Magnetoresistance; Disorder

In recent years, there has been revival of interest for the semi-classical transport two-dimensional electron gas (2DEG) particularly, to the behavior of the magnetoresistance (MR). In the simple situation of a degenerate non-interacting 2DEG the conventional Boltzmann–Drude approach yields zero MR, i.e. the value of longitudinal component of the resistivity tensor ρ_{xx} is magnetic field independent. However, in a pioneering work [1], the importance of non-Boltzmann classical memory effects in magnetotransport of 2DEG with small number of impurities was demonstrated. Only 10 years later a related MR was observed in first antidot lattice experiments [2–5]. The purely classical origin of this MR was fully recognized only recently. This MR may be either negative or positive depending on the type of scattering potential, and is a consequence of memory effects [6–11] both in high ($\omega_c\tau > 1$) [6–10] and weak magnetic fields ($\omega_c\tau < 1$) [11]. Recently, a very important step in our understanding of the role of memory effects in 2D magnetotransport of real systems in strong magnetic field has been made in Ref. [9]. In this paper a theory of the magnetoresistance of 2DEG scattered by a short-range potential in presence of a long-range correlated random potential has been advanced. The most important result of this theory is that the interplay of two types

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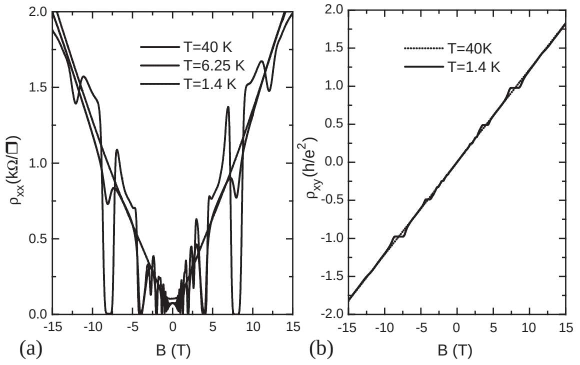

Fig. 1. Dissipative $\rho_{xx}(B)$ (a) and Hall resistivity $\rho_{xy}(B)$ (b) at different temperatures (sample 218).

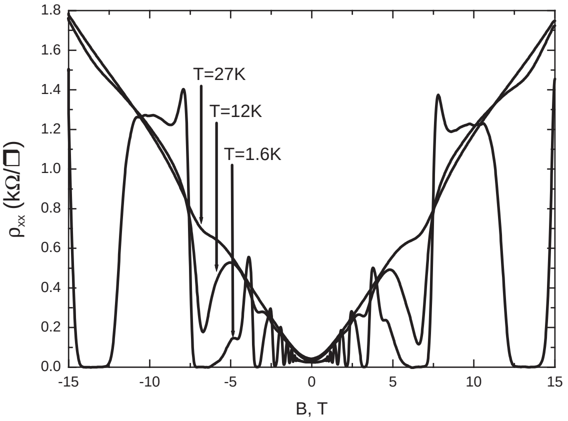

Fig. 2. Dissipative resistivity $\rho_{xx}(B)$ for the sample 188.

of scattering generates new behavior of $\rho_{xx}(B)$ which is absent when only one kind of scattering is present and leads to a positive non-saturating MR.

The purpose of this paper is to report that the experimental behavior of quasi-classical MR in high mobility 2DEG with and without artificial scatters supports the main results of the theory [9]. We observed a giant positive non-saturating MR of 2DEG in AlGaAs/GaAs heterostructure. The dilution of artificial scatters (antidots) in this 2DEG gives a large negative MR in low magnetic field leading to a non-monotonic dependence of $\rho_{xx}(B)$ also predicted in [9].

The samples we studied were: (1) high mobility 2DEG in MBE grown AlGaAs/GaAs heterostructure with 20 nm (sample 188 and 189) and 60 nm (sample 218) spacer thickness; (2) lattices of antidots fabricated on the basis of this 2DEG. The antidot lattices of period $d = 0.6$ μm were fabricated on the basis of 218.

Fig. 1 shows $\rho_{xx}(B)$ and $\rho_{xy}(B)$ for the sample 218 for different temperatures at electron density $N_s = 1.9\times10^{11}$ cm^{-2} (the mobility is μ=4.3×10^5 cm^2/V s at 4.2 K corresponding to $\omega_c\tau = 645$ at 15 T). At the lowest temperature ($T = 1.4$ K) the conventional behavior of high mobility 2DEG is observed. At $B < 1$ T there is a small parabolic-like negative MR (this MR is possibly due to interaction effects [12,13] but will not be discussed here). For $B > 1$ T SdH oscillations appear, then the QHE regime starts with deep minima in $\rho_{xx}(B)$ and corresponding plateaus in $\rho_{xy}(B)$. The basic aim of our study is to measure the resistivity B-dependence in strong magnetic field ($\omega_c\tau \gg 1$) in the regime satisfying to the condition $\hbar\omega_c < 2\pi kT$ and $kT \ll E_F$. According to the usual conception of 2DEG magnetotransport in high magnetic field increasing temperature should lead to (1) the decrease of amplitude of SdH oscillations and their complete suppression at $kT > \hbar\omega_c/2\pi$ and (2) the absence of any significant MR as long as $kT \ll E_F$. Our experiment completely supports the first point: heating to temperatures higher than 17 K leads to the complete disappearance of SdH oscillations. However, we observe a large positive MR (PMR), $\rho_{xx}(B) \sim B^{\alpha}$, non-saturating up to the higher field. It is worth noting that the value of the Fermi energy $E_F = 8$ meV is significantly larger than kT even at the highest temperature 40 K ($kT = 4$ meV at 40 K). So the MR cannot be due to a non-degeneracy of 2DEG at this temperature. Finally, for $B > 8$ T only the first Landau level is occupied. The non-saturating MR is thus observed in the regime of fractionally occupied first Landau level.

The same behavior (except for the range of weak magnetic fields where no negative MR (NMR) is seen) is observed in the sample 188 (see Fig. 2) with a larger electron density N_s=3.1×10^{11} cm^{-2} and mobility μ= 8×10^5 cm^2/V s at 4.2 K corresponding to $\omega_c\tau$=1200 at 15 T. The exponent α for this sample is close to that found in the sample 218. The large non-saturating MR was observed in early studies devoted to high mobility samples ($\mu > 10^5$ cm^2/V s) [14,15]. However, all the previous measurements were performed at temperatures below 4.2 K and the semi-classical MR was not clearly detected. One more important feature: increasing the temperature leads to a significant growth in the ρ_{xx} minima of SdH oscillations but leaves the maxima unchanged. This allows us to conclude that in high mobility 2DEG the transport in quantum Hall regime when the Fermi level lies between two Landau level has mainly semi-classical origin.

Let us now discuss the results described above. We have already noted that in framework of Boltzman approach there should be no significant MR in degenerate 2DEG. In our experiment the value of $\Delta\rho_{xx}(B)/\rho^0_{xx}$ reaches approximately 50 for the sample 218 and 80 for the sample 188 at $B = 15$ T. At the first glance it is not surprising because in high mobility 2DEG in AlGaAs/GaAs heterostructure the scattering by long-range potential dominates and the recently advanced theory [8] of magnetotransport in this potential predicts such behavior. However according to Ref. [8] $\Delta\rho_{xx}(B)/\rho^0_{xx} \leqslant 3$, the MR should shows a maximum at $\omega_c\tau = (100\text{–}200)$ leading to zero resistivity the limit of infinite B. The opposite so-called Lorentz model, which takes only into account the short-range component of the disorder, also predicts a zero resistivity in infinite field. As our experiment shows in a real high mobility 2DEG (where both kind of disorder may exist) we observe non-saturating MR in the achieved range of magnetic fields ($\omega_c\tau$ up to 10^3) which contradicts the two previous models. We think the qualitative explanation of our results is given in Ref. [9]. The most important conclusion of this theory is that the interplay of short-range disorder (random ensemble of impenetrable discs with the size a, density n corresponding to the mean free path l_s) and long-range correlated scattering potential generates new behavior of $\rho_{xx}(B)$ including the appearance of a non-saturating positive semi-classical MR. In the hydrodynamic limit ($a \to 0$, $n \to \infty$, $l_s = \text{const}$) the theory predicts a $\rho_{xx}(B) \sim B^\alpha$ positive MR α depending of the magnetic field range: a first range with $\alpha = 0$, a second with $\alpha = \frac{12}{7}$, in the third $\alpha = \frac{17}{10}$, and in the fourth $\alpha = \frac{10}{13}$. Fig. 3 shows the experimental dependences $\rho_{xx}(\omega_c\tau)/\rho^0_{xx}$ for all three kinds of the samples studied measured at highest temperatures. One can see that the experiment shows slightly another behavior. For all samples (188, 189 and 218) we observe a first range for which $\rho_{xx}(\omega_c\tau)/\rho^0_{xx} = \text{const}$ and then a transition to the $\rho_{xx}(\omega_c\tau)/\rho^0_{xx} \sim B^\alpha$ dependence with $\alpha = 0.9\text{–}1.2$, increasing with the growth of the magnetic field. There is nothing surprising in the obtained difference between the experiment and the theory because hydrodynamics limit is an idealized picture. Also for $T > 20$ K a significant contribution of the phonon scattering appears and can modify $\rho_{xx}(B)/\rho^0_{xx}$.

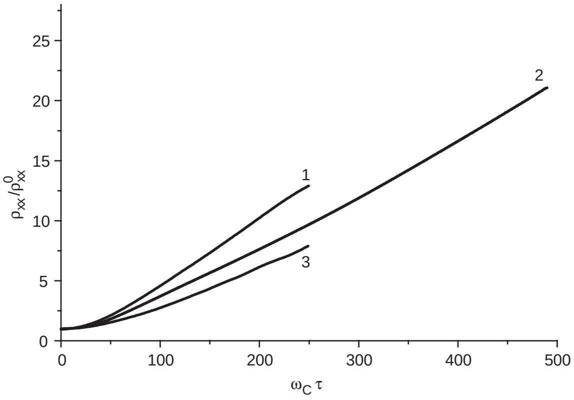

Fig. 3. ρ_{xx}/ρ^0_{xx} as function of $\omega_c\tau$ (1–188, $T = 27$ K; 2–218, $T = 40$ K; 3–189, $T = 27$ K).

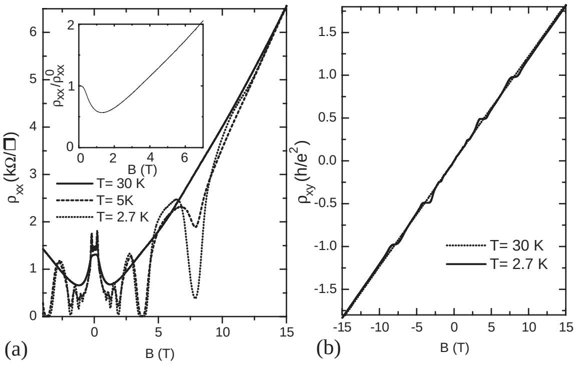

Fig. 4. Dissipative resistivity $\rho_{xx}(B)$ (a) and Hall resistivity $\rho_{xy}(B)$ (b) at different temperatures (antidot lattice). Inset shows the dependence.

A very interesting prediction is given by the theory in the case of dilute antidot array: a NMR should be observed in intermediate field leading to non-monotonic dependence $\rho_{xx}(B)$. Fig. 4 shows the experimental $\rho_{xx}(B)$ and $\rho_{xy}(B)$ measured in antidot lattice at temperatures 2.7–30 K. For high temperatures when SdH oscillations are suppressed the experimental $\rho_{xx}(B)$ is non-monotonic. For $B < 1.2$ T the predicted negative MR is observed, it turns to a non-saturating PMR;

which is similar to that of in the unpatterned 2DEG. The Hall resistance behaves in the same way as in usual antidot lattices. The insert in Fig. 4a shows $\rho_{xx}(B)/\rho^0_{xx}$ at 30 K. One can see that qualitatively the result is similar to that obtained in the theory [9]. However, the detailed dependence $\rho_{xx}(B)/\rho^0_{xx}$ obtained analytically (see part C of Ref. [9]) does not coincide with the experimental one; neither for the NMR part nor for the PMR part. We do not observe the $\rho_{xx}(B)\sim B^{-1}\ln B$ NMR and we do not observe the value $\alpha = \frac{12}{7}$ for positive part of the experimental curve near $\rho_{xx}(B)$ minimum: the experiment shows $\rho_{xx}(B/\rho^0_{xx})\sim B^{-\alpha}$ (α=0.3–0.6) and $\rho_{xx}(B)/\sim B^{0.9}$ (see the insert to Fig. 4). Thus theory [9] gives a correct description of the general shape of $\rho_{xx}(B)$ for both the unpatterned samples and for antidot lattices: a positive non-saturating MR in the first case and non-monotonic MR in the second case. However, the detailed dependences in the theory and the experiment differ. This disagreement may be explained by the fact that the theory gives an idealized picture. Furthermore, it considers (in the case of antidot lattice) random arrays of antidots while in our experiment the lattice is periodic.

In conclusion, we have shown that the quasi-classical MR of the high mobility 2DEG in AlGaAs/GaAs heterostructure is very large and non-saturating up to values of $\omega_c\tau$ amounting to 10^3. In antidot lattice we observe a non-monotonic behavior of the MR being negative first and non-saturating and positive then with a similar dependence to that of unpatterned samples. The comparison of experimental results with the theory [9] gives a satisfactory qualitative agreement.

Acknowledgements

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