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Large positive magneto-resistance in high mobility 2D electron gas: interplay of short and long range disorder

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We have observed a large positive quasi-classical magneto-resistance (MR) in a high mobility 2D electron gas in AlGaAs/GaAs heterostructure. The magneto-resistance is non-saturating and increases with magnetic field as $\rho_{xx} \sim B^\alpha$ ($\alpha = 0.9 - 1.2$). In antidot lattices a non-monotonic MR is observed. We show that in both cases this MR can be qualitatively described in terms of the theory recently advanced by Polyakov *et al* (PRB, **64**, 205306 (2001)). Their prediction is that such behavior as we observe may be the consequence of a concurrent existence of short and long range scattering potentials.

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I. INTRODUCTION

In recent years, there has been a revival of interest for the semi-classical transport properties of a two-dimensional electron gas (2DEG) particularly for the behavior of the classical magneto-resistance (MR). On one hand, it is due to the technological progress in the preparation of high mobility heterostructures, 2DEGs with artificial scattering and modulating potential, antidot lattices, weak modulated one-dimensional structures, and so on. On the other hand, a remarkable progress has been made recently in the theoretical understanding of the importance of memory effects in semi-classical magneto-transport. In the simplest situation of a degenerated non-interacting 2DEG with isotropic Fermi surface the conventional Boltzmann-Drude approach yields zero magneto-resistance, i.e. the value of the longitudinal component of the resistivity tensor ρ_{xx} does not depend on magnetic field. However, already in the pioneering work of Ref. 1 the importance of non-Boltzmann classical memory effects in magneto-transport of 2DEGs with a small a number of impurities was demonstrated and a large negative MR was predicted. More than ten years later this MR was observed in experiments performed in antidot lattices²⁻⁵. However it's only recently that the purely classical origin of this MR was fully recognized. This MR may be either negative or positive depending on the type of the scattering potential, and it appears as a consequence of the memory effects⁶⁻¹¹ both in high ($\omega_c > 1$)⁶⁻¹⁰ and weak magnetic fields ($\omega_c < 1$)¹¹. Recently a very important step in the understanding of the role of memory effects in the magneto-transport of a real 2DEG in strong magnetic field was done in Ref. 9. In this paper the theory of the magneto-resistance of a 2DEG scattered by a short -range disorder potential in the 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 of scattering

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

The purpose of this paper is to report that the experimental behavior of the quasi-classical MR in high mobility 2DEGs in AlGaAs/GaAs heterostructure with and without artificial scatters agrees well with the main results of the theory⁹. We have observed a large positive non-saturating MR of the 2DEG and the addition of artificial scatters (antidots) in this 2DEG results in a negative MR in intermediate fields that leads a non-monotonic dependence of $\rho_{xx}(B)$ predicted in Ref. 9.

II. EXPERIMENTAL SET UP

The samples we studied were: 1) high mobility 2DEGs in MBE grown AlGaAs/GaAs heterostructures with a spacer thickness of 40 nm (sample 188 and 189) and 60 nm (sample 218); 2) lattices of antidot fabricated on the basis of this 2DEG. The parameters of the 2DEG at $T=4.2$ K were the following: sample 188 - $\mu = (5 - 10) * 10^5 \text{cm}^2/\text{Vs}$ at electron densities $N_s = (3 - 5) * 10^{11} \text{cm}^{-2}$; sample 189 - mobility $\mu = 1.2 * 10^6 \text{cm}^2/\text{Vs}$ at $N_s = 6 * 10^{11} \text{cm}^{-2}$ and sample 218 - $\mu = (3 - 6) * 10^5 \text{cm}^2/\text{Vs}$ at electron densities $N_s = (1 - 2) * 10^{11} \text{cm}^{-2}$. An antidot lattice with the period $d=0.6 \mu\text{m}$ was fabricated on the basis of sample 218 by means of electron lithography and consequent plasma etching. The samples were measured at $T = (1.5 - 40) \text{K}$ in magnetic fields up to 15 T using superconducting magnet and a Variable Temperature Insert. The data was acquired using standard low frequency lock-in technique.

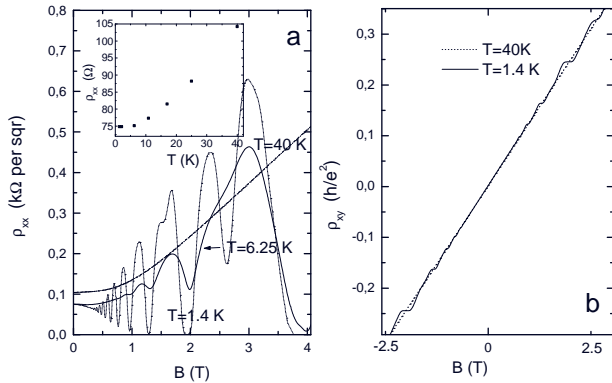


FIG. 1: Dissipative (a) and Hall resistivity of sample 218 at different temperatures. Insert to (a) show the zero-field T -dependence of ρ_{xx}

III. RESULTS AND ANALYSIS

Fig. 1a shows $\rho_{xx}(B)$ for the sample 218 at different temperatures in magnetic fields up to 4 T at the electron density $N_s = 1.9 \times 10^{11} \text{cm}^{-2}$ (The mobility is $\mu = 4.3 \times 10^5 \text{cm}^2/\text{Vs}$ at 4.2 K so that $\omega_c\tau = 215$ at 5 T and the mobility is $\mu = 3 \times 10^5 \text{cm}^2/\text{Vs}$ at 40 K with $\omega_c\tau = 150$ at 5 T). The Hall resistance $\rho_{xy}(B)$ under the same conditions is presented in Fig. 1b. At the lowest temperature ($T = 1.4$ K) the conventional behavior for high mobility 2DEGs is observed.

For low temperature and for $B < 1$ T there is a small parabolic-like negative MR (possibly due the interaction effects^{13,14} not discussed here), then the Subnikov de Haas (SdH) oscillations appear, and finally the Quantum Hall Effect sets in with deep minima in $\rho_{xx}(B)$ and corresponding plateaus in $\rho_{xy}(B)$. Note that our aim here is to study the MR dependence in strong magnetic field ($\omega_c\tau \gg 1$) but at the same time in the quasi-classical regime satisfying the conditions $\hbar\omega_c < kT, kT \ll E_F, N > 1$ (N is the number of occupied Landau level). According to the usual conception of the magneto-transport in high magnetic field the increase of temperature should lead to: 1) a decrease in the amplitude of SdH oscillations and their complete suppression for $kT > \hbar\omega_c$ and 2) the absence of any significant magneto-resistance as long as $kT \ll E_F$. As one can clearly see from Fig. 1a our experiment completely supports the first point: Heating the sample to temperatures higher than 17 K leads to a complete disappearance of SdH oscillations. However instead of a B -independent resistivity a large positive non-saturating MR (PMR) develops. Note that the value of the Fermi energy is $E_F = 8$ meV for sample 218, $E_F = 16$ meV for sample 188 and $E_F = 31$ meV for sample 189 which are significantly larger than kT even at highest temperature 40 K ($kT = 3.5$ meV at 40 K). So the MR can be not attributed to a non-degeneracy of the 2DEG at this temperature. The

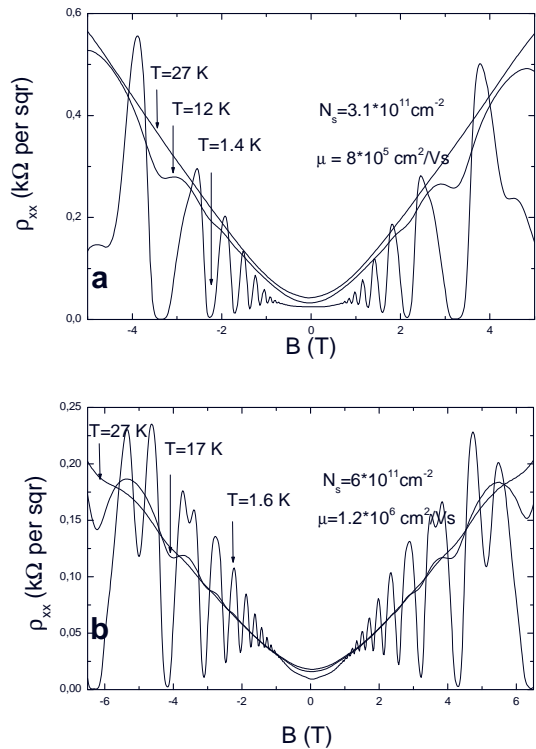


FIG. 2: Dissipative resistivity at different temperatures for sample 188 (a) and 189 (b)

same behavior (except for the low field range where there is no parabolic NMR unlike for sample 218) is observed in samples 188 and 189 with larger electron densities and mobilities ($N_s = 3.1 \times 10^{11} \text{cm}^{-2}$, $\mu = 8 \times 10^5 \text{cm}^2/\text{Vs}$ and $N_s = 6 \times 10^{11} \text{cm}^{-2}$, $\mu = 1.2 \times 10^6 \text{cm}^2/\text{Vs}$ at $T = 4.2$ K respectively for 188 and 189. See Fig. 2a and 2b).

The ordinary oscillating dependence of $\rho_{xx}(B)$ transforms to a monotonic dependence $\rho_{xx}(B) \sim B^\alpha$ when the temperature is increased. The value of α is close to the value found for sample 218. Fig. 3 summarizes the results for all samples: $\Delta\rho_{xx}(\omega_c)/\rho_0$ are plotted (the curves are displayed in order to keep the condition $N > 1$ satisfied).

One can see that even if the low magnetic field features are different (the start of positive MR occur at different values of B) the high magnetic field behaviors are similar: $\Delta\rho_{xx}(\omega_c)/\rho_0 \sim B^\alpha$ with $\alpha=0.9-1.1$ (close to $\alpha = 1$). A large non-saturating MR was actually observed in earlier papers devoted to high mobility ($\mu > 10^5 \text{cm}^2/\text{Vs}$) 2DEGs^{15,16}. However all measurements were performed at temperatures $T \leq 4.2$ K and the semi-classical MR was not clearly detected because of the oscillating dependence

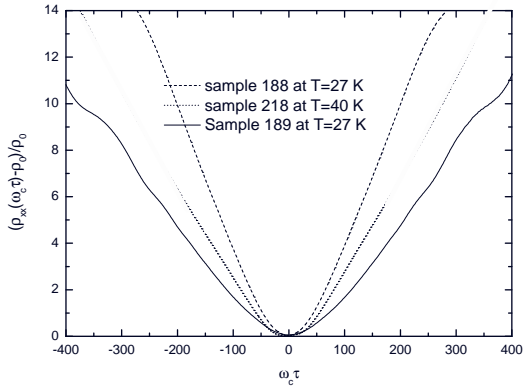


FIG. 3: Magnetoconductance $\Delta\rho_{xx}(\omega_c)/\rho_0$ in the quasi-classical regime for all three samples

of $\rho_{xx}(B)$. As mentioned above in the framework of the Boltzmann approach there should be no significant MR in degenerated 2DEGs ($E_F \gg kT$). The value of the MR in this case is of the order of $\Delta\rho_{xx}(B)/\rho_{xx} \approx (kT/E_F)^2$ so we should not observe a value of $\Delta\rho_{xx}(B)/\rho_0$ exceeding 10% even at 5 T. On the contrary in our experiment the value of $\Delta\rho_{xx}(B)/\rho_{xx}$ reaches approximately 10-15 for all samples (see Fig. 3), i.e almost 10^2 times larger. At first glance this result is not so surprising; indeed a theory of magneto-transport in a long range scattering potential (which is the case for high mobility 2DEGs in AlGaAs/GaAs heterostructures) has recently been proposed⁸. It predicts a positive MR. However according to this theory $\Delta\rho_{xx}(B)/\rho_0 < 3$ and, more importantly, it predicts a maximum around $\omega_c\tau = (100 - 200)$ and then a negative MR which is the sign of the localization of electrons in the limit $B \rightarrow \infty$. As one can see from Fig. 3 we observe no saturation even at $\omega_c\tau$ as high as $(3 - 4) * 10^2$. So we are in the interesting following situation: Theoretically it is predicted that if only one kind of scattering potential is present (short range or long range) there should be either no MR at all or a negative MR in the limit of infinite magnetic field (indicating the localization in this limit). On the contrary, as our experiment reveals, in a real high mobility 2DEG there is a non-saturating MR in the achieved range of magnetic fields ($\omega_c\tau = 4 * 10^2$). More over we do not observe the maximum predicted in intermediate field (around $\omega_c\tau=(100-200)$) by the theory⁸ and we obtain values of $\Delta\rho_{xx}/\rho_0$ much higher than predicted in Ref. 8. Also note that quantum calculation in the framework of Born approximation¹² can give a positive MR at high temperatures (when SdH Oscillations are washed out) but the value of α is then 0.5 not around 1 as we observe.

We think that the qualitative explanation of our results is given in Ref. 9 where the theory of a semi-classical magneto-transport in 2DEGs with both kinds of disorder potential has been advanced. The more important con-

clusion of this theory is that the interplay of short range disorder (random ensemble of impenetrable discs of diameter a and density n) and long-range correlated disorder generates a new behavior of $\rho_{xx}(B)$ including the appearance of a non-saturating positive semi-classical MR. The author shows that the localization ($\rho_{xx} \rightarrow 0$ when $B \rightarrow \infty$) induced by the presence of only one kind of disorder is destroyed by the presence the other kind of disorder. In this theory the short range scattering is characterized by the mean free path l_s and the long range scattering by l_L . In the hydrodynamic limit ($a \rightarrow 0, n \rightarrow \infty, l_s = const$) the theory gives four ranges of magnetic field dependence for the positive MR. In the first range $\rho_{xx} = const$, as B is increased ρ_{xx} turns to $\rho_{xx} \sim B^{12/7}$, then to $\rho_{xx} \sim B^{10/7}$ and finally to $\rho_{xx} \sim B^{10/13}$. Qualitatively the experiment shows a similar behavior (see Fig. 1 and Fig. 2). But a more detailed comparison shows that there are some differences: For the sample 218 we observe a first range with $\rho_{xx} = const$ and then a transition to the dependence $\rho_{xx} \sim B^\alpha$ with $\alpha = 0.9-1.1$ increasing with the magnetic field (this value is slightly larger than 10/13). For the sample 188 and 189 the picture is different: at weak magnetic fields there is no $\rho_{xx} = const$ range, instead we observe $(\rho_{xx}/\rho_0 - 1) \sim B^2$ and at magnetic fields where $\rho_{xx}(B)/\rho_0 \gg 1$ the behavior is the same as for sample 218.

There is nothing surprising in the observed difference between the experiment and the theory because the hydrodynamic limit is a very idealized picture and the scattering potential in a real high mobility 2DEG is much more complicated. Also it is necessary to note that at temperatures $T \geq 20$ K a significant contribution (see the insert to Fig. 1a) of the phonon scattering appears that can modifies the dependence $\rho_{xx}(B)$ too. Obviously phonon scattering should not radically change the situation principally because phonon scattering plays the same role as short range scattering. Nevertheless an accurate description of the experiment at high temperatures requires a theory including phonon scattering.

A very interesting prediction of the theory is given for antidot arrays. In this case the theory predicts a negative MR in intermediate magnetic fields leading to a non-monotonic dependence of $\rho_{xx}(B)$.

Fig. 4a shows the experimental dependence $\rho_{xx}(B)$ measured in an antidot lattice, fabricated on the basis of sample 218 at temperatures between 1.4 K and 40 K for $N_s = 1.8 * 10^{11} cm^{-2}$. The Hall resistance measured under the same conditions is shown in Fig. 4b. One can see from the insert to Fig. 4a that at high enough temperatures (when SdH oscillations are suppressed) the experimental curve $\rho_{xx}(B)$ demonstrate a non-monotonic behavior. For $B < 1.2$ T a Negative MR which is due to the formation of rosette trajectories is observed. This NMR is then replaced by a non-saturating positive MR, which is similar to the positive MR observed in the unpatterned 2DEG. A the same time the Hall resistance shows no extra-features evolving

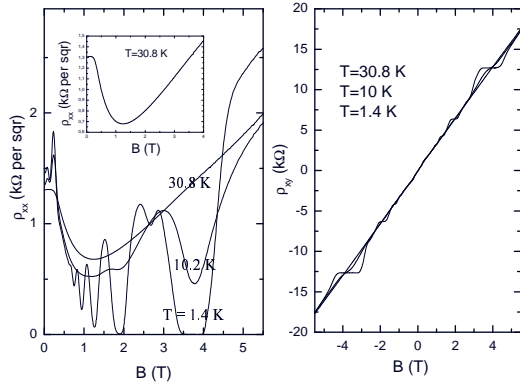


FIG. 4: Dissipative (a) and Hall resistivity of the antidot lattice at different temperatures

from a curve with plateaus into straight line when the temperature is increased (same behavior as in unpatterned samples). Qualitatively the behavior is well described by theory⁹. However the detailed dependence of $\rho_{xx}(B)$ obtained from analytical calculation (see part III C from Ref. 9) does not coincide with the experimental one neither for the negative MR nor for the positive MR. We do not observe the $\rho_{xx}(B) \sim B^{-1} \ln(B)$ for NMR and the value $\alpha = 12/7$ for PMR of the experimental curve near $\rho_{xx}(B)$ minimum. The experiment shows $\rho_{xx}(B) \sim B^{-1/2}$ and $\rho_{xx}(B) \sim B^{0.9}$. One of the possible reasons of this disagreement is that the theory considers a random array of antidots while our experiment is performed in a periodic lattice.

Anyway the position of the minimum in $\rho_{xx}(B)$ dependence for the antidot lattice is interesting to analyze. The theory gives the following condition at the minimum:

$$\zeta/R_{cm} \approx p^{-4/19} [n\zeta^2 \ln(1/n\zeta^2 p^{1/3})]^{7/19}$$

Where $p = l_s/(l_L \zeta)^{1/2}$, l_s is the mean free path in

the short range potential, l_L is the mean free path in the long range potential, n is the density of antidots, ζ is the correlation length of the long range potential and R_{cm} is the cyclotron radius at the minimum. For our lattice parameters we obtain $\zeta \approx 100$ nm in other words $k_F \zeta \geq 10$; that is to say that the parameters obtained from the analysis of the position of the minimum in terms of the theory⁹ corresponds to long range potential scattering. Thus theory⁹ gives a good description of the main experimental features of $\rho_{xx}(B)$ both for an unpatterned high mobility 2DEG and for a 2DEG with an antidot lattice: positive non-saturating MR in the first case and non-monotonic MR in the second case. However the detailed dependencies given in the theory and obtained in the experiment differ.

IV. CONCLUSION

In conclusion, we have shown that the quasi-classical MR of a high mobility 2DEG in AlGaAs/GaAs heterostructure is very large and non-saturating up to values of $\omega_c \tau$ exceeding 300. The magnetic field dependence of $\rho_{xx}(B)$ follows the law $\rho_{xx}(B) \sim B^\alpha$ ($\alpha=0.9-1.1$). In antidot lattices we observe two ranges of magnetic fields dependence leading to a non-monotonic behavior of the MR (negative first and then positive and non-saturating with a dependence a close to that observed in unpatterned samples). The comparison of experimental results with the theory⁹ gives satisfactory agreement.

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