Large positive magnetoresistance in a high-mobility two-dimensional electron gas: Interplay of short- and long-range disorder

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We have observed a large positive quasiclassical magnetoresistance (MR) in a high mobility two-dimensional electron gas in an AlGaAs/GaAs heterostructure. The magnetoresistance is nonsaturating and increases with magnetic field as $\Delta\rho_{xx} \sim B^{\alpha}$ ($\alpha = 0.9-1.2$). In antidot lattices a nonmonotonic 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.* [Phys. Rev. B **64**, 205306 (2001)]. Their prediction is that the behavior 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 in the semiclassical transport properties of a two-dimensional electron gas (2DEG) particularly for the behavior of the classical magnetoresistance (MR). On one hand, it is due to the technological progress in the preparation of high mobility heterostructures, 2DEG's 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 semiclassical magnetotransport. In the simplest situation of a degenerated noninteracting 2DEG with an isotropic Fermi surface the conventional Boltzmann-Drude approach yields zero magnetoresistance, i.e., the value of the longitudinal component of the resistivity tensor ρ_{xx} does not depend on magnetic field. However, in the pioneering work of Ref. 1 the importance of non-Boltzmann classical memory effects on the magneto-transport of 2DEGs with a small a number of impurities has already been demonstrated and a large negative MR was predicted. More than ten years later this MR was observed in experiments performed in antidot lattices.[2–5] However, it is 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 memory effects[6–11] both in high ($\omega_c > 1$) (Refs. 6–10) and weak magnetic fields ($\omega_c < 1$).[11] Recently a very important step in the understanding of the role of memory effects on the magnetotransport of a real 2DEG in strong magnetic field was done in Ref. 9. In this paper the theory of the magnetoresistance 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 potential generates a behavior of $\Delta\rho_{xx}(B)$ absent when only one kind of disorder is present, and leads to a positive nonsaturating MR.

The purpose of this paper is to compare the experimental behavior of the quasiclassical MR in high mobility 2DEG's in AlGaAs/GaAs heterostructure with and without artificial scatters to the theory.[9] We have observed a large positive nonsaturating MR of the 2DEG and the addition of artificial scatters (antidots) in this 2DEG results in a negative MR in intermediate fields that leads the nonmonotonic dependence of $\Delta\rho_{xx}(B)$ predicted in Ref. 9.

II. EXPERIMENTAL SETUP

The samples we studied were (1) high mobility 2DEG's in MBE grown AlGaAs/GaAs heterostructures with a spacer thickness of 40 nm (samples 188 and 189) and 60 nm (sample 218), and (2) lattices of antidots fabricated on the basis of this 2DEG. The parameters of the 2DEG at $T = 4.2$ K were the following: sample 188, $\mu = (5-10) \times 10^5$ cm^2/V s at electron densities $N_s = (3-5) \times 10^{11}$ cm^{-2}; sample 189, mobility $\mu = 1.2 \times 10^6$ cm^2/V s at $N_s = 6 \times 10^{11}$ cm^{-2}; and sample 218, $\mu = (3-6) \times 10^5$ cm^2/V s at electron densities $N_s = (1-2) \times 10^{11}$ cm^{-2}. The samples were photolithographically processed into 50 μm Hall bars with the distance between the four voltage probes on each side 100, 250, and 100 μm and Ohmic contacts to the Hall bars were prepared by annealing of AuNiGe. An antidot lattice with the period $d = 0.6$ μm was fabricated on the basis of sample 218 with Hall bars on it by means of electron lithography and consequent plasma etching. The samples were measured at $T = (1.5-40)$ K in magnetic fields up to 15 T using a superconducting magnet and a variable temperature insert. The data was acquired using standard low-frequency lock-in technique.

III. RESULTS AND ANALYSIS

Figure 1(a) shows $\rho_{xx}(B)$ for the sample 218 at different temperatures in magnetic fields up to 15 T at the electron density $N_s = 1.9 \times 10^{11}$ cm^{-2}. (The mobility is $\mu = 4.3$

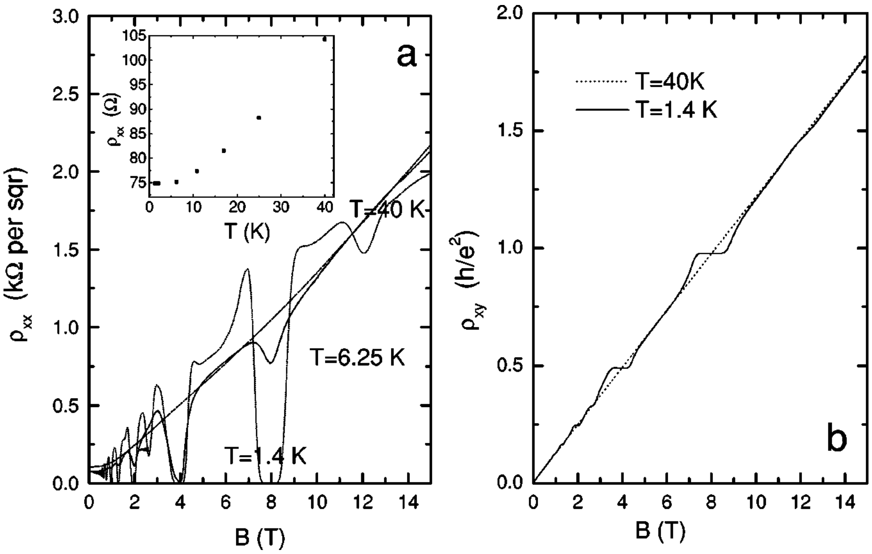

FIG. 1. Dissipative (a) and Hall resistivity (b) of sample 218 at different temperatures. The inset to (a) shows the zero-field T dependence of ρ_{xx}.

$\times 10^5$ cm^2/V s at 4.2 K so that $\omega_c\tau=215$ at 5 T and the mobility is $\mu=3\times 10^5$ cm^2/V s 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. 1(b).

At the lowest temperature ($T=1.4$ K) the conventional behavior for high mobility 2DEG's is observed: For $B<1$ T there is a small paraboliclike negative MR (possibly due to 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 $\rho_{xy}(B)$. For high temperatures we observe the disappearance of the SdH oscillations and the magnetoresistance turning to $\Delta\rho_{xx}(B)/\rho_0\sim B^{\alpha}$ with α close to 1. The same behavior (except for the low field range where there is no parabolic NMR) is observed in samples 188 and 189 with larger electron densities and mobilities ($N_s=3.1\times 10^{11}$ cm^{-2}, $\mu=8\times 10^5$ cm^2/V s, and $N_s=6\times 10^{11}$ cm^{-2}, $\mu=1.2\times 10^6$ cm^2/V s at $T=4.2$ K, respectively, for 188 and 189) [see Figs. 2(a) and 2(b)]. The value of α is close to the value found for sample 218.

A large nonsaturating MR was actually observed in earlier papers devoted to high mobility $\mu>10^5$ cm^2/V s 2DEG's.[15,16] However, all measurements were performed at temperatures $T\leqslant 4.2$ K and the semiclassical MR was not clearly detected because of the oscillating dependence of $\rho_{xx}(B)$. Our aim here is to study the MR dependence in strong magnetic field ($\omega_c\tau\gg 1$) in the high temperatures quasiclassical regime (i.e., $\hbar\omega_c/2\pi<kT, kT\ll E_F, N>1$, N is the number of occupied Landau levels). According to the usual conception of the magnetotransport 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 $kT>\hbar\omega_c/2\pi$ and (2) a weak magnetic field dependence of the resistance as long as $kT\ll E_F$. In this regime $\Delta\rho_{xx}(B)/\rho_0\approx(kT/E_F)^2$ so we should not observe a value of $\Delta\rho_{xx}(B)/\rho_0$ exceeding 10% even at 5 T.

Figures 1(a) and 2 show that our experiment completely supports the first point: Heating the samples to temperatures higher than 20 K leads to the complete disappearance of SdH oscillations. However our high-T experiments reveal

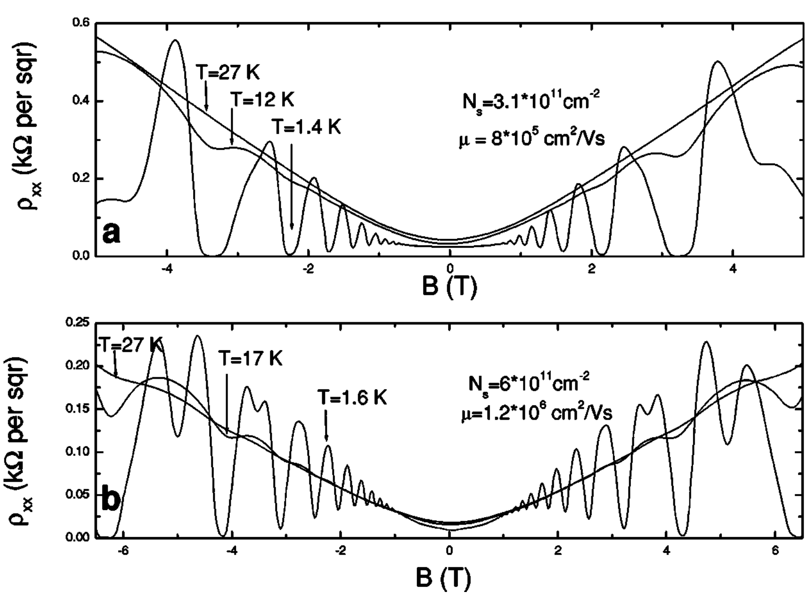

FIG. 2. Dissipative resistivity at different temperatures for samples 188 (a) and 189 (b).

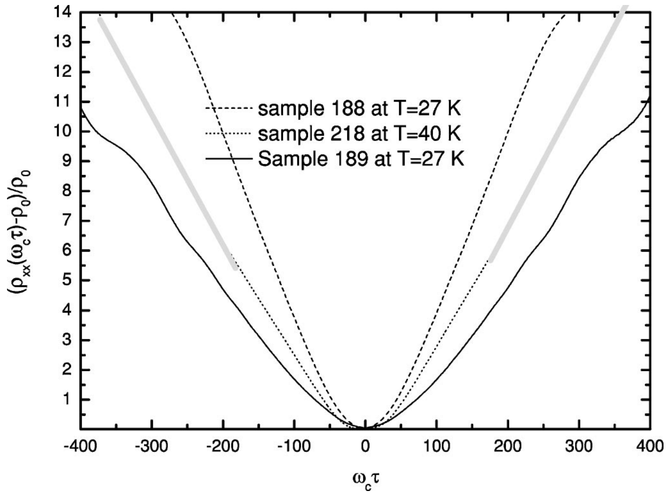

FIG. 3. Magnetoresistance $\Delta\rho_{xx}(\omega_c)/\rho_0$ in the quasiclassical regime for all three samples.

$\Delta\rho_{xx}(B)/\rho_0$ as high as 10–15 for all our samples, a clear contradiction with the second assumption.

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 the highest temperature 40 K ($kT=3.5$ meV at 40 K). So the MR is not attributed to a nondegeneracy of the 2DEG at this temperature. More over, as can be clearly seen from Fig. 2 the curves are very symmetric and the possibility of mixing between the hall and longitudinal signals can be excluded.

Figure 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). At first glance this result is not surprising; indeed a theory of magnetotransport in a long-range scattering potential (which is the case for high mobility 2DEG's in AlGaAs/GaAs heterostructures) has recently been proposed.[8] It predicts a positive MR. However, according to this theory $\Delta\rho_{xx}(B)/\rho_0<3$ and, more importantly, $\Delta\rho_{xx}(B)/\rho_0$ should show a maximum around $\omega_c\tau=(100-200)$ and go to zero in the limit of infinite fields (this is the sign of the localization of electrons in this limit).

Figure 3 shows that we observe no saturation even at $\omega_c\tau$'s as high as $(3-4)\times10^2$. So we are in the interesting following situation. Theoretically it is predicted that if only one kind of scattering potential is present (short or long range) there should be either no MR at all or a negative MR in the limit of infinite magnetic field. On the contrary we observe a large ($\Delta\rho_{xx}/\rho_0\sim10$) nonsaturating magnetoresistance. Note that a quantum calculation in the framework of the Born approximation[12] can give a positive MR at high temperatures (when SdH oscillations are washed out) but the value of the exponent α is then 0.5, not around 1 as we observe, so the theoretical framework completely fails to explain our data.

A qualitative explanation of our results might be given in the recent work of Ref. 9 where the theory of semiclassical magnetotransport in 2DEG's with both kinds of disorder potentials (which is always the case in any sample) has been advanced. The more important conclusion of this theory is that the interplay of short- (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 nonsaturating positive semiclassical MR. The authors show that the localization ($\rho_{xx}\to0$ when $B\to\infty$) induced by the presence of only one kind of disorder is destroyed by the presence of the other kind. 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 ($a\to0, n\to\infty, l_s=$const) the theory gives four ranges of magnetic field dependence for the positive MR. In the first range $\Delta\rho_{xx}=0$, as B is increased $\Delta\rho_{xx}$ turns to $\Delta\rho_{xx}\sim B^{12/7}$, then to $\Delta\rho_{xx}\sim B^{10/7}$, and finally to $\Delta\rho_{xx}\sim B^{10/13}$. Qualitatively the experiment shows a similar behavior (see Figs. 1 and 2). But a more detailed comparison shows that there are some differences. For sample 218 we observe a first range with $\Delta\rho_{xx}=0$ and then a transition to the dependence $\Delta\rho_{xx}\sim B^{\alpha}$ with $\alpha=0.9-1.1$ increasing with the magnetic field (this value is slightly larger than 10/13). For samples 188 and 189 the picture is different: at weak magnetic fields there is no $\Delta\rho_{xx}=0$ range, instead we observe $(\rho_{xx}/\rho_0-1)\sim B^2$ and at magnetic fields where $\rho_{xx}(B)/\rho_0\gg1$ the behavior is the same as for sample 218. There is nothing surprising in the observed difference between the experiment and 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 note that at temperatures $T\geqslant20$ K a significant contribution [see the inset to Fig. 1(a)] of the phonon scattering appears that can modify the magnetic field dependence of ρ_{xx}. 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 nonmonotonic dependence of $\rho_{xx}(B)$. Figure 4(a) shows the experimental dependence $\rho_{xx}(B)$ measured in an antidot lattice, fabricated on the basis of sample 218 at temperatures between 1.4 and 40 K for $N_s=1.8\times10^{11}$ cm^{-2}. The Hall resistance measured under the same conditions is shown in Fig. 4(b). The inset to Fig. 4(a) reveals that at high enough temperatures (when SdH oscillations are suppressed) the experimental curve $\rho_{xx}(B)$ demonstrates a nonmonotonic behavior. For $B<1.2$ T a negative MR due to the formation of rosette trajectories is observed. This NMR is then replaced by a nonsaturating positive MR, which is similar to the positive MR observed in the unpatterned 2DEG's. A the same time the Hall resistance shows no extra features evolving from a curve with plateaus into a straight line when the temperature is increased (the same behavior as in unpatterned samples). Qualitatively the behavior is well described by theory.[9] However, the detailed dependence of $\rho_{xx}(B)$ obtained from analytical calculations (see Sec. III C from Ref. 9) does not coincide with the experimental data; neither for the negative MR nor for the positive MR and the theory fails to describe the details of our data. We do not observe the $\rho_{xx}(B)\sim B^{-1}\ln(B)$ for NMR and

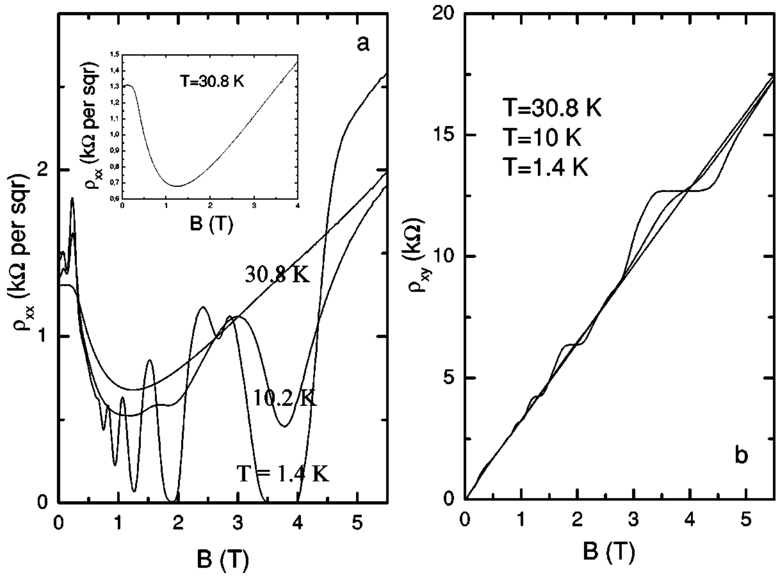

FIG. 4. Dissipative (a) and Hall resistivity (b) of the antidot lattice at different temperatures.

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.

Even if it fails to accurately describe our data the theory predicts a minimum and it is interesting to compare the position of the experimental minimum to this prediction. Indeed its position depends on the correlation length of the long-range potential and of the average density of antidots independently of the arrangement of the antidots. 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. This value is close to the spacer thickness (60 nm) which is known to determine the correlation length of the long-range potential.

IV. CONCLUSION

In conclusion, we have shown that the quasiclassical MR of a high mobility 2DEG in AlGaAs/GaAs heterostructure is very large and nonsaturating 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 a non-monotonic behavior of the MR (negative first and then positive and nonsaturating similar to that observed in unpatterned samples). The comparison of the experimental results with the theory[9] gives satisfactory qualitative agreement but the theory fails to describe the details of the magnetoresistance traces.

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