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High-field magnetoresistance in a periodically modulated two-dimensional electron gas

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We have extended earlier measurements of the magnetoresistance in a periodically modulated two-dimensional electron gas to high magnetic fields, where the cyclotron radius, r_c, is much smaller than the period, a, of modulation. A giant nonoscillatory magnetoresistance was found to arise beyond the range of low-field (Weiss) oscillations periodic in $1/B$. Its value in a magnetic field of a few tesla may exceed the zero-field resistance value, ρ_0, by 1 to 2 orders of magnitude. This result is in agreement with the semiclassical theory by Beenakker, if a modulation of the electron mobility is taken into account.

The recent observation of low-field magnetoresistance oscillations in two-dimensional electron gas (2DEG) systems with submicron periodicity[1] has already generated a considerable interest of several groups.[2-8] Currently, attention has been paid to the oscillations periodic in $1/B$ and other features[4-9] in low magnetic fields, where the condition $2r_c > a$ holds. However, even the curves emphasizing low fields, which are presented in many publications hint a pronounced positive magnetoresistance in fields higher than the region of the low-field oscillations. This magnetoresistance, however, is usually concealed by the Shubnikov–de Haas (SHdH) oscillations. The high-field magnetoresistance in a modulated 2DEG has not previously been discussed in the literature, presumably because it has not been considered an intrinsic property of the system. However, its existence follows directly from expressions obtained in Ref. 10, which were used to describe the Weiss oscillations. It is the main purpose of this paper to show how this magnetoresistance is a direct consequence of the density and mobility modulation of the 2DEG.

For two different geometries [one-dimensional (1D) and two-dimensional (2D) modulations] and increasing the degree of modulation, we observed a pronounced increase of the longitudinal resistance in high magnetic fields, $2r_c < a$. A square magnetoresistance in our 1D geometry and a nearly linear one for the 2D case continues up to the quantizing fields, where the quenching of the longitudinal resistance due to a transport along the edge states is obviously essential. If the 1D modulation potential is weak the magnetoresistance can be described by the semiclassical theory.[10] The magnetoresistance in Ref. 10 has been attributed to a formation of drifting electron orbits in regions with a rapidly varying density of the 2DEG, so that the Fermi velocity, v_F, changes significantly on the scale of r_c. In high fields this extended (drifting[10] or streaming[9]) motion leads to a magnetoresistance analogous to the motion along the open orbits occurring in some normal metals.[11]

The first kind of structures used in the experiment was a conventional Hall bar device fabricated from a GaAs/$Ga_{0.7}Al_{0.3}As$ heterostructure with a 2DEG having a mobility of $\mu \simeq 30\ m^2V^{-1}s^{-1}$, a concentration of $n = 5.1 \times 10^{15}\ m^{-2}$, and a distance from the surface of 70 nm. Using electron-beam lithography a one-dimensional periodic pattern with a period of $a = 1\ \mu m$ was formed in a negative resist providing a nearly full modulation of its thickness. This resist then served as a dielectric for a metal gate evaporated on top of the device. In Fig. 1 the magnetoresistance of the 2DEG subjected to an increase of the 1D modulation by applying a negative gate bias is shown. The low-field oscillations periodic in $1/B$ were small in this relatively low-mobility device since the condition $\mu B \gg 1$ does not hold for the needed magnetic field range, $2r_c > a$.[9,10] On the curves with the nonzero gate voltage V_g applied, we observed the last two minima of these oscillations in accordance with the condition, $2r_c = (m - \frac{1}{4})a$ with $m = 1,2$.[1] These minima are hardly seen on the scale of Fig. 1 at the relevant magnetic fields less than 0.5 T. In higher fields a square magnetoresistance is seen, which rapidly increases with increasing gate voltage. A similar behavior may be found on draft curves of Ref. 4. A further increase of the magnetic field leads to a more complicated magnetoresistance behavior due to the formation of edge states and the subsequent quenching of the

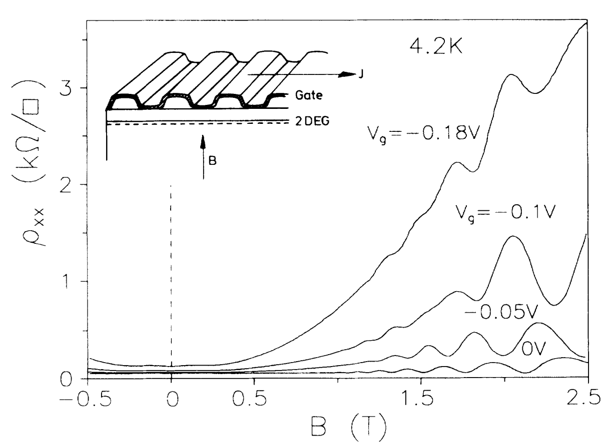

FIG. 1. Magnetoresistance traces at 4 K for a GaAlAs heterostructure with a one-dimensional grating gate. Different curves correspond to an increase of the negative gate bias, which modulates the two-dimensional electron gas. A schematic picture of the sample is shown in the inset. The modulation period is $a = 1\ \mu m$.

longitudinal magnetoresistance.

A similar high-field magnetoresistance shown in Figs. 2(a) and 2(b) has been also observed for high-mobility samples with a 2D modulation. A square array of metal spots was fabricated on the heterostructure surface by electron-beam lithography [spot diameter $d \simeq 100$ nm with a period $a \simeq 250$ nm; see Fig. 2(a), inset]. For comparison, samples without a pattern and with a complete metal gate cover were fabricated during the same technological processes. The unpatterned sample had a mobility $\mu \simeq 100$ $m^2 V^{-1} s^{-1}$ and a sheet concentration of electrons $n \simeq 2.8 \times 10^{15}$ m^{-2}. Two samples with the spot pattern were measured. They had a 4% smaller concentration and a 30% lower mobility (in zero magnetic field) while the sample totally covered by metal (aluminum) had $n \simeq 2.1 \times 10^{15}$ m^{-2} and $\mu \simeq 18$ $m^2 V^{-1} s^{-1}$. Applying a negative gate voltage $V_g = -0.1$ V to the latter sample we found a conductance pinchoff, while a positive bias rapidly increased the mobility when the 2DEG increased its concentration. The above data convincingly show that regions with the latter characteristics are formed underneath the metal spots in the patterned sample. The decrease of concentration in the gated regions is caused by an additional band bending at the boundary between GaAs and Al.

Figure 2(a) shows two magnetoresistance traces; one for an unprocessed high-mobility sample and the other for the same sample with a two-dimensional array of spots. A practically linear magnetoresistance between 0.2 T ($r_c \simeq a$) and the onset of ShdH oscillations is seen in the modulated structure. The magnetoresistance curves for samples with a 2D modulation exhibits some weak features at low magnetic fields, which correspond to the commensurability between the cyclotron radius and the superlattice period.[6,7] These features cannot be distinguished in a scale of Fig. 2, and they are not the matter of the following considerations. The magnetoresistance behavior becomes clearer at higher temperatures, since the Shubnikov-de Haas oscillation amplitude decreases (Fig. 3). The fact that the positive magnetoresistance was not influenced by temperature indicates that we are dealing with a classical transport phenomenon. We could change the modulation of the 2DEG by illuminating the sample. A light-emitting diode was placed far from the sample surface providing a diffuse illumination. Since the spot diameter of the two-dimensional array was smaller than the wavelength of the light used, almost no shadows were expected. Thus, illumination increased the concentration of electrons almost evenly over the 2DEG. Yet a slight modulation of n is expected to remain after a full illumination as a consequence of the different GaAs band

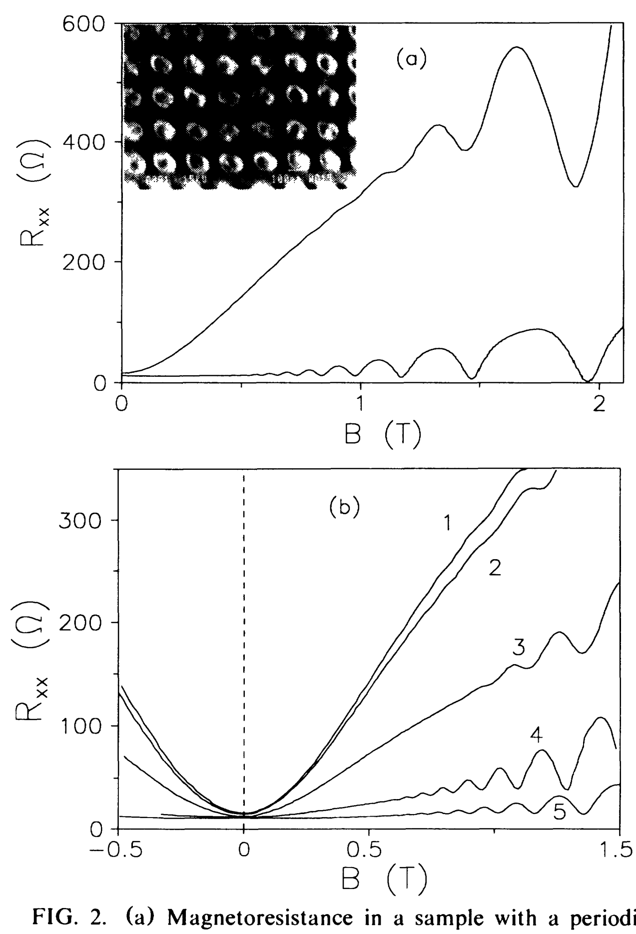

FIG. 2. (a) Magnetoresistance in a sample with a periodic two-dimensional array of submicron spots (upper curve). A micrograph of the pattern is shown in the inset, the period is $a = 0.25$ μm. The lower curve shows the magnetoresistance for the same heterostructure without a pattern on the surface. (b) Magnetoresistance of the two-dimensional modulated sample shown in the inset of (a) under illumination with red light. The illumination time increases from the top and decreases the modulation of the electron mobility and concentration. Curve No. 1, unilluminated sample; No. 2, 0.1 sec of illumination; No. 3, 0.5 sec; No. 4, 3 sec; No. 5, 300 sec.

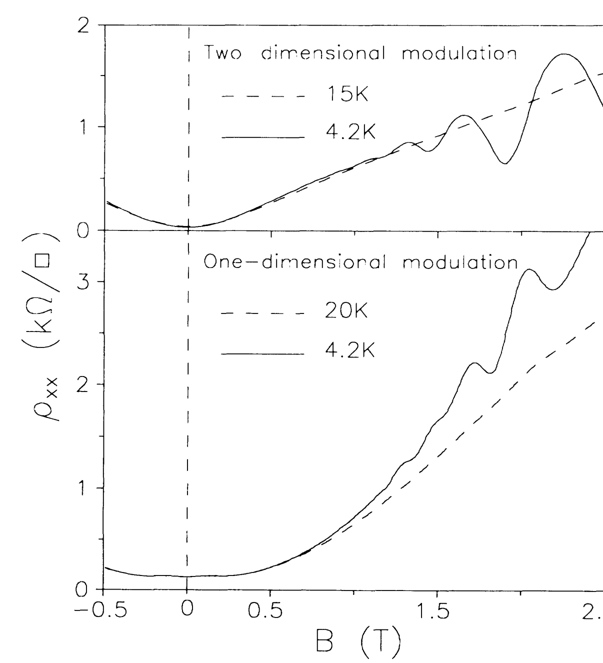

FIG. 3. Magnetoresistance traces for samples with two-dimensional (upper panel) and one-dimensional (lower panel) modulations at two different temperatures. For the 1D sample $V_g = -0.18$ V.

bending conditions due to the Al spots. A set of curves for increasing the illumination dose (in the sequence 1 to 5) is shown in Fig. 2(b) demonstrating a permanent decrease of the linear magnetoresistance. There was a rapid decrease of the magnetoresistance during the first few seconds of illumination [curves 1–4 in Fig. 2(b)], and then the magnetoresistance changed very slowly reaching its saturation (curve 5) after about 5 min of illumination. The rapid decrease of the magnetoresistance magnitude with illumination indicates that the original strong (6 times) modulation of the mobility is at first affected. Actually, the slight increase of the electron concentration after the first seconds of illumination mainly even out the mobility modulation. The further increase of concentration is expected mainly to affect the magnetoresistance due to the density modulation. Some small magnetoresistance (about one zero-field resistance, ρ_0, per tesla) remained even after the full illumination and is attributed to the remaining modulation caused by the band bending in the GaAs introduced by the metal spots.

To explain the Weiss oscillations, Beenakker derived the following expression, valid for a small modulation of the electron density, $\delta n/n$, and for $\omega_c\tau \gg 1$,[10]

$$\frac{\rho_{xx}}{\rho_0}=1+0.5\left(\frac{\delta n}{n}\right)^2 (ql)^2 J_0^2(qr_c)[1-J_0^2(qr_c)]^{-1}, \quad (1)$$

where $q=2\pi/a$ and l is the mean free path. If $r_c \ll a$, this formula turns into $\rho_{xx}/\rho_0 = 1+(\delta n/n)^2\omega_c^2\tau^2$. The experimental curves in Figs. 1 and 3 (lower panel) fit well to the square law up to the quantizing magnetic fields. The absolute magnitude of the magnetoresistance also fits Eq. (1) well. For the sample shown in Fig. 4, we have determined the threshold voltage V_t, where the modulation of the electron density goes to zero, to be $V_t=-0.4$ V. At $V_g=0$ V there is no modulation. $\delta n/n$ in Eq. (1) represents the relative root-mean-square (rms) modulation, which is $2\sqrt{2}$ times smaller than the peak to peak value V_g/V_t. Also the prefactor $(ql)^2$ depends on the modulation, since we find that the conductance and thus the mean free path decrease rapidly with the negative gate voltage as seen in Fig. 1. For the experiment shown in Fig. 4 the zero-field resistance has increased by a factor 2.5 relative to the unmodulated case and the mean free path is therefore $l \cong 1$ μm for $V_g=-0.18$ V, in contrast to $l=3$ μm for $V_g=0$ V. It is important to take into account the mean free path l in Eq. (1) to explain the experiments. In the upper inset of Fig. 4 we show the coefficient of the magnetoresistance (per square magnetic field measured in tesla) plotted as a function of the gate voltage calculated by Eq. (1) with no adjustable parameters. The experimentally found magnetoresistance exceeds the theoretical results by about a factor of 1.5. This is hardly surprising since Eq. (1) assumes a sinusoidal modulation of the electron density, whereas the experiment differs significantly from this assertion. The calculated fit to the magnetoresistance versus the $\omega_c\tau$ curve in Fig. 4 uses Eq. (1) with $\Delta\rho/\rho$ proportional to $J_0(qr_c)^2[1-J_0(qr)^2]^{-1}$ and gives a very good fit to the experimental curves below $\omega\tau \approx 40$, where we can neglect the Shubnikov–de Haas oscillations.

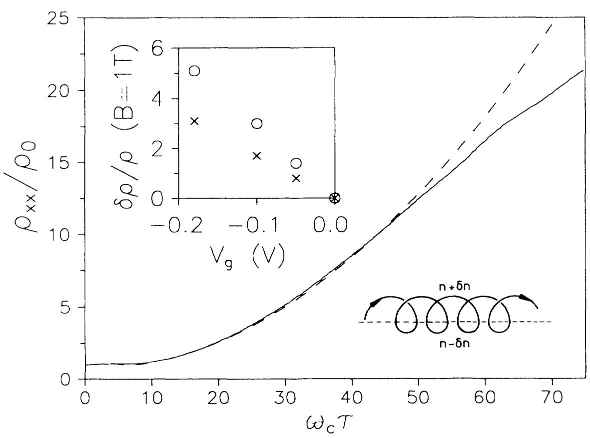

FIG. 4. A comparison between experiment (solid curve; the 1D modulated sample at 20 K and $V_g=-0.18$ V) and theoretical expression $(\rho_{xx}-\rho_0)/\rho_0 \sim J_0(qr_c)^2[J_0(qr_c)^2-1]$ (dashed curve). In the upper inset the experimentally determined magnetoresistance coefficient (per square tesla) is shown as circles for different modulation strengths (gate voltages). The crosses are the calculated magnetoresistance coefficient using Eq. (1) in the text without any adjustable parameters. The lower inset shows the skipping elorbits along the boundary between regions with different electron concentrations. Scattering of the skipping orbit is dominated by the side of the interface with the highest scattering rate.

The modulation of the mobility can be introduced similar to Beenakker's considerations but in the following more transparent way. First, let us rephase the way of obtaining the magnetoresistance from the modulation of n.[10] The drifting motion of electrons along the boundary between regions having different concentration, $n-\delta n$ and $n+\delta n$, is shown in Fig. 4 (lower inset). A distortion of the circular orbit due to the difference in cyclotron radii, $\delta r_c = r_c(\delta n/n)$, leads to a drift of the guiding center with the velocity $v_d = 2\delta r_c\omega_c/2\pi = (v_F/\pi)(\delta n/n)$ (here we imply $\delta n \ll n$). For the unmodulated 2DEG, the diffusion coefficients are $D_{xx}=D_{yy}=D_0[1+(\omega_c\tau)^2]^{-1}$ and $D_{xy} = -D_{yx} = (\omega_c\tau)D_{xx}$, where $D_0=\frac{1}{2}v_F^2\tau$. The drift of electrons along the 1D modulation potential causes the additional term, $\delta D_{yy} \simeq \tau v_d^2$. Employing the Einstein relation, $\hat{\rho}=(h^2/4\pi me^2)\hat{D}^{-1}$ $[\rho_{xx}=(h^2/4\pi me^2)D_{yy}/(D_{xx}D_{yy}+D_{xy}^2)]$ one can calculate the resistivity. For instance, it is easy to obtain $\rho_{xx}/\rho_0 \simeq (\delta n/n)^2\omega_c^2\tau^2$ in the $\omega_c\tau \gg 1$ case, i.e., the same as derived from Eq. (1). For electrons drifting along the density boundary, the relaxation rate is determined roughly by the rate in the region with the lowest mobility, i.e., $\tau=\tau_{dp}$, where τ_{dp} is the mean free time in the depleted region. Values of τ_{dp} can be found directly from the increase of the zero-field resistance ρ_0, when the gate voltage is applied. Taken into account the mobility changes, we calculated the magnetoresistance as a function of V_g as shown in the inset of Fig. 4.

For a regular fourfold symmetric 2D modulation, which is the result of the metallization shown in the inset of Fig. 2(a), the magnetoresistance is expected to differ essentially from the 1D case, since in this case there is no guiding of the electrons in one direction. Unless the electrons can follow open orbits at the Fermi surface in k space in high magnetic fields or there is an exact compensation of electrons and holes, it is well known[11] that there will always be a saturation of the magnetoresistance at high magnetic fields. However, we cannot simply use a two-band model to calculate the magnetoresistance because we have first to take into account the two-dimensional periodic potential in the properties of the electrons. A semiclassical model in which the electrons are trapped in skipping orbit around each spot in the two-dimensional array gives a qualitative answer, however. Since $\delta D_{xx}=\delta D_{yy}$ both saturates for a 2D modulated sample and largely exceeds $D_{xy}\sim(\omega_c\tau)^{-1}$, it is expected that the $\rho_{xx}\sim D_{yy}/(D_{xx}D_{yy}+D_{xy}{}^2)$ should saturate in high magnetic fields. The expected fields correspond to $\omega_c\tau\gg(\delta n/n)^{-2}$, which coincides in our case with the range of the edge state transport. Employing the above model, which has already been used for the 1D modulation, we obtained a reasonable correspondence to the experimental behavior. The linear magnetoresistance shown in Figs. 2 and 3 corresponds approximately to a region where the magnetoresistance goes from a square law to saturation. However, the detailed behavior for the 2D modulated sample cannot be explained in this simple model. The experiment shows that removing the mobility modulation by shining light on the sample decreases the magnetoresistance, as expected. Another qualitative view on the magnetoresistance for a two-dimensional modulation is that the electrons cannot go all the way to infinity along a concentration boundary like in the one-dimensional case, but moves around the spots if l/a is large and $a/r_c\rightarrow\infty$. So, some relaxation rate is needed to provide the diffusion of electrons along the sample in contrast to the 1D case, where electrons can go off to infinity without any scattering at all. Thus, one may expect a nonmonotonic behavior of the magnetoresistance versus $\omega_c\tau$ for the 2D case. It would be of interest to expand the semiclassical theory to the 2D case beyond the low-field oscillation region.

In conclusion, we observed a large magnetoresistance in a laterally modulated 2DEG, at fields higher than corresponding to the low-field oscillations periodic in $1/B$. This magnetoresistance results from drifting motion of cyclotron orbits in regions of the 2DEG, where the electron concentration varies. For the strongly modulated 2DEG, an additional modulation of electron mobility was found to change essentially the value of the magnetoresistance. Taking into account both the modulation of mobility and density, good agreement between the experiment and theory was obtained for the 1D modulation potential.

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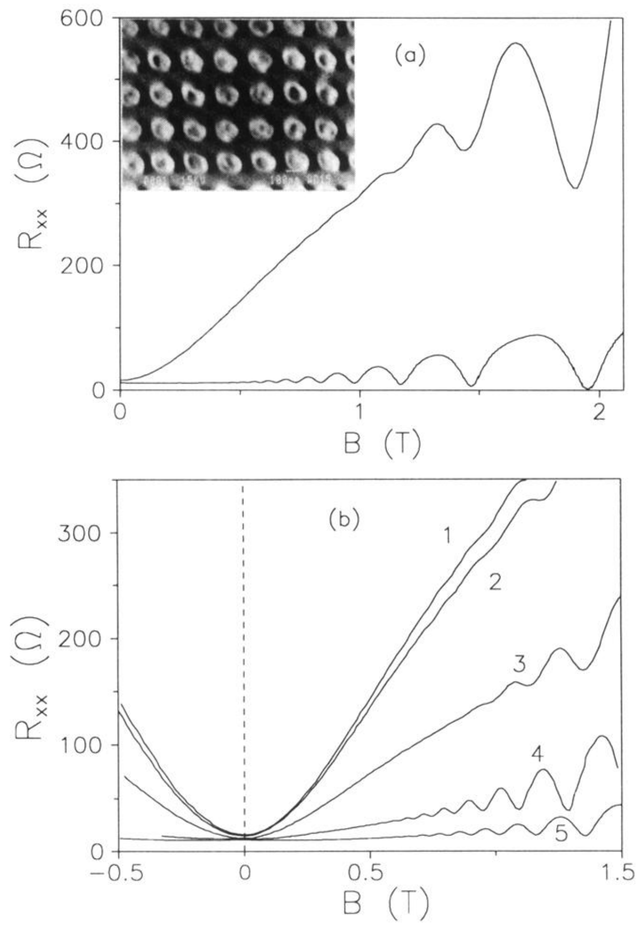

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