Landau-Band Conductivity in a Two-Dimensional Electron System Modulated by an Artificial One-Dimensional Superlattice Potential

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We investigate the magnetoresistance of a quasi-two-dimensional electron system subject to a one-dimensional superlattice potential created by the field effect in gated AlGaAs/GaAs heterojunctions. At low temperatures this potential gives rise to a new type of magnetoresistance oscillation with a period governed by the ratio of the classical cyclotron diameter $2R_c$ to the superlattice period a. The oscillations are quantitatively explained in period, phase, and magnitude by the formation of Landau bands in the two-dimensional electron system under the influence of the periodic potential.

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Until recently experimental investigations of the effect of a lateral superlattice potential on the electronic transport properties of a two-dimensional electron system (2D ES) have been limited to "natural" superlattices in metal oxide-semiconductor structures on high-index surfaces of Si [1,2] or InSb.[3] Modulation-doped AlGaAs/GaAs heterojunctions with a 2D ES of high mobility now make it possible to study lateral superlattice phenomena using artificially created potentials with periods in the submicrometer range. As a first manifestation of such one-dimensional (1D) superlattice effects Weiss *et al.*[4] recently observed a new type of oscillation of the low-temperature magneotresistance at magnetic fields $B<1$ T applied perpendicularly to the 2D ES of an AlGaAs/GaAs heterojunction with a weak periodic electron density modulation. They created the modulation via the persistent photoeffect by exposing the sample to a light grating of submicrometer period a. Similar to Shubnikov–de Haas (SdH) oscillations these new resistance oscillations are periodic in $1/B$. Weiss *et al.* found that apart from a phase factor ϕ, maxima in the magnetoresistance arise whenever the classical cyclotron diameter $2R_c$ at the Fermi energy is a multiple of the period a such that

$$2R_c=(m+\phi)a,\quad m=1,2,\ldots. \tag{1}$$

In their report, however, they did not identify the mechanism causing the oscillations.

Here we present experimental studies of these novel magnetoresistance oscillations on AlGaAs/GaAs heterojunctions with a periodically microstructured gate electrode, in which the field effect is used to create a 1D periodic potential. We demonstrate that the magnetoresistance oscillations reflect the formation of Landau bands in the 2D ES under the influence of the superlattice potential. Calculating the magnetic band structure in the presence of the periodic potential,[5,6] we show that the bandwidth of the Landau bands at the Fermi energy oscillates periodically with period $2R_c/a$ and gives rise to an oscillatory band conductivity. We calculate the magnetoresistance caused by this mechanism and find good agreement with the observed oscillations in period, phase, and magnitude.

The samples are prepared on conventional AlGaAs/GaAs heterojunctions grown by molecular-beam epitaxy. The heterojunctions consist of a 1.6-μm-thick GaAs buffer on top of a semi-insulating GaAs substrate, a 20-nm nominally undoped $Al_xGa_{1-x}As$ ($x=0.33$) spacer, a 50-nm-thick Si-doped $Al_xGa_{1-x}As$ layer, and a 9-nm undoped GaAs caplayer. On the heterojunction we holographically define a grating of period $a=500$ nm consisting of photoresist stripes about 200 nm wide and 130 nm high and evaporate a thin NiCr layer as gate electrode.[7] A schematic cross section of the sample is shown in Fig. 1(a). Two Hall bar-shaped samples oriented parallel and perpendicular to the grating, respectively, are defined by wet etching and have gated areas 200 μm wide and 750 μm long. Source-drain contacts and potential probes are evaporated In/Ag layers alloyed at 420 °C. At 4.2 K and gate voltage $V_g=0$ V the inversion layer has a 2D electron density $N_s^0=3.2\times10^{11}$ cm^{-2} and mobility $\mu=e\tau_t/m^*$ as determined from the dc conductivity σ_0 of $\mu=350000$ $cm^2/(V\ sec)$, corresponding to an elastic mean free path of $l_{el}=v_F\tau_t=3.3$ μm.

Application of a voltage at the periodic gate structure causes a 1D periodic potential leading to an electron density modulation. At large negative gate bias (here $V_g\leq-0.45$ V) the electron system becomes a grating of parallel 1D inversion channels.[7,8] Here we consider the regime of small V_g, i.e., small potential modulation. Using four-point probing we measure the diagonal components of the resistivity tensor, namely ρ_{xx} and ρ_{yy}, in a magnetic field perpendicular to the 2D ES at liquid-

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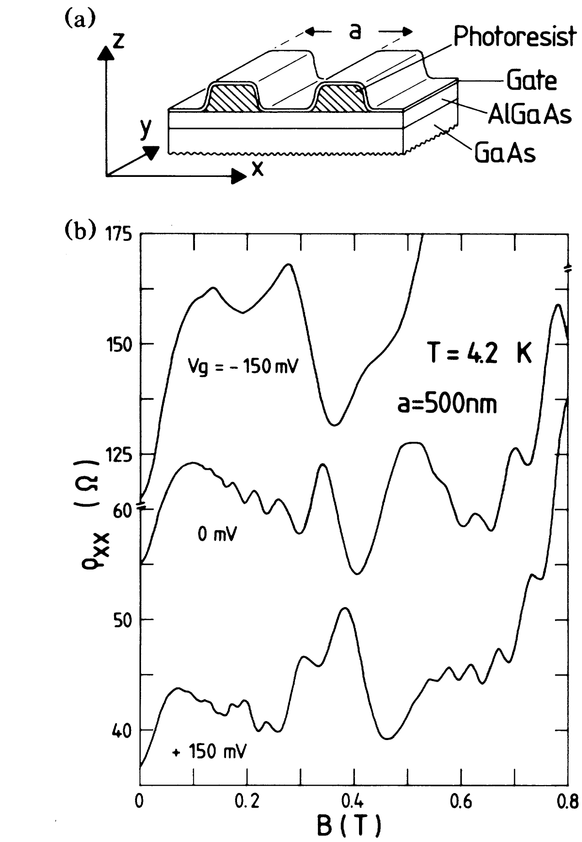

FIG. 1. (a) Schematic cross section of a heterojunction with a periodic gate structure. (b) Measured ρ_{xx} vs magnetic field B for three different gate voltages V_g.

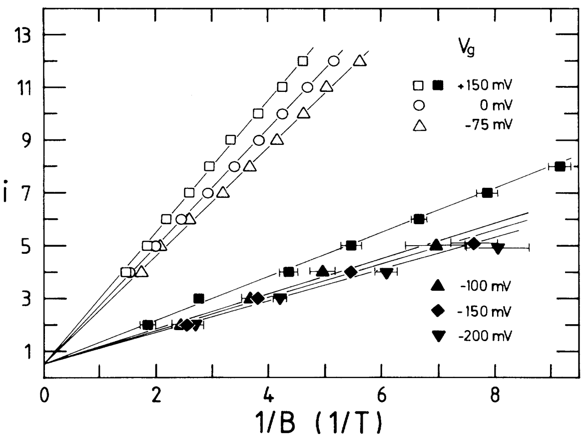

FIG. 2. Fan diagram of the position of the magnetoresistance extrema vs $1/B$ for the low-field oscillations at different gate voltages V_g. Here i is an arbitrary running index and odd (even) for resistance maxima (minima). Filled symbols denote the oscillations belonging to the fundamental period $a=500$ nm whereas open symbols are used for the oscillations belonging to $a/3$. The lines are calculated from Eqs. (1) and (2) using N_s values determined from SdH oscillations and phase factors $\phi=+0.25$ (-0.25) for maxima (minima).

helium temperatures. Figure 1(b) shows the magnetoresistance component ρ_{xx} along the superlattice versus B for different V_g. At $B>0.5$ T we observe SdH oscillations that are a measure of the electron density N_s. At $V_g \neq 0$ V the magnetocapacitance exhibits two oscillation periods $\Delta(1/B)$ reflecting the different densities N_{s1} and N_{s2} below the two regions of the gate period, respectively, whereas the SdH oscillations of ρ_{xx} yield an average $N_s \approx (N_{s1}+N_{s2})/2$.

In Fig. 1(b) at $B<0.5$ T we observe additional oscillations in ρ_{xx} which are the central issue here. These oscillations are much smaller in ρ_{yy}, in agreement with Weiss *et al.*[4] As best seen at $V_g=150$ mV, the ρ_{xx} oscillations contain two distinct periods. These periods are immediately visible if one plots an arbitrary running index i versus the position of the extrema of the magnetoresistance on a $1/B$ scale as in Fig. 2. For a quantitative evaluation we calculate the cyclotron diameter at the Fermi energy, using the average N_s as determined above:

$$2R_c = 2(2\pi N_s)^{1/2}(\hbar/eB)\,. \tag{2}$$

One oscillation period is found to correspond to maxima of ρ_{xx} at $2R_c=[m+(0.18\pm0.07)]a$ and minima at $2R_c=[m-(0.26\pm0.06)]a$, where $m=1,2,\ldots,$ and $a=492\pm39$ nm, in excellent agreement with the grating period. The second period, which is the prominent one at $V_g=0$ V, corresponds to maxima of ρ_{xx} at $2R_c=[m+(0.26\pm0.05)]b$ and minima at $2R_c=[m-(0.21\pm0.05)]b$ with $b=168\pm24$ nm$=a/3$. We defer discussion of this third-harmonic period to later and now explain the origin of the fundamental period $2R_c/a$ which dominates ρ_{xx} at negative V_g and is also clearly visible at $V_g=+150$ mV.

In the magnetic field regime of interest here we have $\omega_c\tau_t>1$ ($\omega_c\tau_t=1$ at $B=0.03$ T) where $\omega_c=eB/m^*$ is the cyclotron frequency. Since the field is sufficiently small we neglect quantization of the Hall resistance ρ_{xy} and have with $|\rho_{xy}|\simeq B/eN_s$ and $|\rho_{xy}|\gg\rho_{xx}\simeq\rho_{yy}$:

$$\sigma_{yy}=\frac{\rho_{xx}}{\rho_{xx}\rho_{yy}-\rho_{xy}\rho_{yx}}\simeq\rho_{xx}\frac{N_s^2e^2}{B^2}\,. \tag{3}$$

The magnetoresistance ρ_{xx} perpendicular to the grating thus reflects the parallel conductivity σ_{yy}.

In the Landau gauge with $\mathbf{A}=(0,xB,0)$ we calculate the magnetic band structure of a 2D ES subject to a weak periodic potential $V(x)=V\cos(2\pi x/a)$ by first-order perturbation theory[5] and obtain, with Landau index N, the energy spectrum

$$E_N(k_y)=(N+\tfrac{1}{2})\hbar\omega_c+\langle Nk_y|V(x)|Nk_y\rangle\,.$$

The wave vector $k_y=x_0/l^2$ is a measure of the center coordinate x_0 of the Landau orbit with magnetic length $l=(\hbar/eB)^{1/2}$. The periodic potential along x thus causes

k_y dispersion of the originally discrete Landau levels, i.e., Landau bands similar to those in layered superlattices.[6] Here the relevant Landau indices N are rather high ($N \simeq 12$ at $V_g = 0$ V and $B = 0.5$ T) and we replace the above matrix element by the classical expectation value,

$$\langle V(x)\rangle \simeq \int_{x_0-R_c}^{x_0+R_c} \frac{V\cos(2\pi x/a)}{\pi[R_c^2-(x-x_0)^2)]^{1/2}}dx\,.$$

Here we use $R_c = (2N+1)^{1/2} l$ as a measure of the Landau index N. The integral is solved by the Bessel function J_0 and yields magnetic bands

$$E_N(x_0) = (N+\tfrac{1}{2})\hbar\omega_c + VJ_0\left(\frac{2\pi R_c}{a}\right)\cos\left(\frac{2\pi x_0}{a}\right). \quad (4)$$

For $2\pi R_c/a \gtrsim 1$ we can approximate J_0 by a cosine function

$$J_0\left(\frac{2\pi R_c}{a}\right) \simeq \left(\frac{a}{\pi^2 R_c}\right)^{1/2}\cos\left(\frac{2\pi R_c}{a}-\frac{\pi}{4}\right). \quad (5)$$

The Landau band structure and the density of states in the absence of scatterers is sketched in Fig. 3. The zeros of J_0 give Landau indices N where the Landau bands are flat. With Eq. (5) we find to a good precision the values of $2R_c$ where the Landau level bandwidth Δ at the Fermi energy is extremal. The bandwidth Δ vanishes at $2R_c = (m-0.25)a$ and is maximal for $2R_c = (m+0.25)a$.

The k_y dispersion of the Landau bands Eq. (4) causes a nonvanishing band conductivity σ_{yy}^b even when $\omega_c\tau_t \gg 1$, i.e., in the regime where the usual magnetoconductivity $\sigma^t \simeq \sigma_0/(1+\omega_c^2\tau_t^2)$ is made possible only by scatterers. In the relaxation-time approximation and assuming spin degeneracy we may write

$$\sigma_{yy}^b = \sum_N e^2\tau_b \int_{k_y} \frac{dk_y}{\pi} v_g^2(k_y)\left(-\frac{\partial f}{\partial E}\right)_{E=E_N(k_y)}.$$

where τ_b is an appropriate relaxation time, $v_g = (dE/dk_y)/\hbar$ is the group velocity, and f is the Fermi distribution function. In inversion layers on GaAs the single-particle relaxation time τ_s that determines the width of a Landau level is much shorter[9-11] than the scattering time τ_t, and also, for $B \lesssim 0.5$ T, $\hbar\omega_c$ is of order kT. Therefore we use the high-temperature approximation to obtain

$$\sigma_{yy}^b = \frac{e^2\tau_b}{\hbar\omega_c}\int\frac{dk_y}{\pi}v_g^2(k_y)\,.$$

Using Eqs. (4) and (5) to calculate v_g we finally obtain the band conductivity

$$\sigma_{yy}^b \approx \frac{V^2}{Ba}\frac{e^2\tau_b}{m^*}\frac{2m^{*2}}{\pi e\hbar^3}\frac{\cos^2[2\pi R_c/(a-\frac{1}{4}\pi)]}{(2\pi N_s)^{1/2}}. \quad (6)$$

This band conductivity directly reflects the periodic modulation of the bandwidth Δ of the Landau bands at the Fermi energy and gives an oscillatory resistivity term ρ_{xx}^b that shows the essential features of the observed magnetoresistance oscillations.

To calculate σ_{yy}^b for our experiment we first have to estimate the amplitude V of the first Fourier component of the effective superlattice potential. We obtain V via $V = \Delta N_s/D(E_F)$ from the measured density modulation $\Delta N_s = |N_{s1} - N_{s2}|/2$ extracted from the magnetocapacitance using the $B=0$ density of states $D(E_F)$ of the 2D ES. We find $V \simeq (4.75\ \text{meV/V})V_g$, in good agreement with a calculation of the effective superlattice potential using Thomas-Fermi screening.[12] We neglect nonlinear screening[13] that may be important at high magnetic fields. The scattering time τ_b in Eq. (6) is a measure of

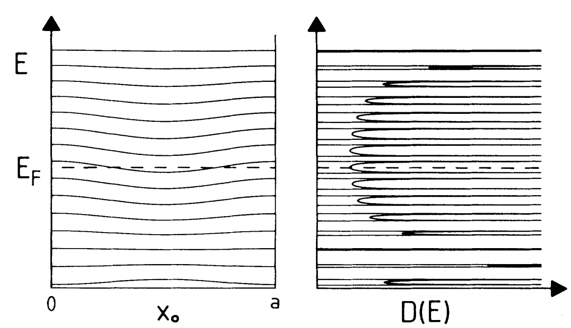

FIG. 3. Sketch of the dispersion of the Landau bands $E_N(x_0)$ (left) and the corresponding density of states $D(E)$ (right) for maximal bandwidth at the Fermi energy E_F.

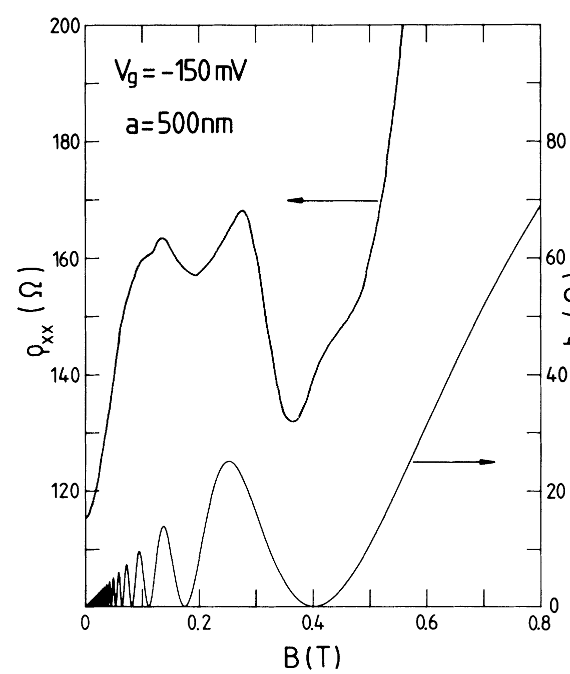

FIG. 4. Comparison of measured magnetoresistance ρ_{xx} (left scale) and calculated band contribution ρ_{xx}^b (right scale) at $V_g = -150$ mV.

the relaxation of the center coordinate x_0 over distances of order a and is expected to increase with decreasing R_c, i.e., increasing B. As a simplest approximation at $R_c \sim a/2$ we may use $\tau_b \approx \tau_t$. With those values of V and τ_b we use Eqs. (3) and (6) to calculate the band contribution ρ_{xx}^b. In Fig. 4 we compare with the experimental trace of ρ_{xx} at $V_g = -150$ mV where $N_s = 2.3 \times 10^{11}$ cm^{-2}, $\tau_t = 10$ ps, and $R_c = a/2$ at $B = 0.3$ T. Considering the simplicity of our model we find the agreement with the experimentally observed amplitude of the ρ_{xx} oscillations astonishingly good. We also note that our model explains why the oscillations are predominantly observed in ρ_{xx} and are much weaker in ρ_{yy}.

It now is obvious that the oscillations dominant at $V_g = 0$ V reflect the third Fourier component of the effective potential oscillating with period $a/3$. At present we have no quantitative explanation for these oscillations. Since they are present at $V_g = 0$ V they seem to be connected either with charge in the photoresist or a Schottky barrier. Assumption of a square-wave-modulated effective surface potential[12] with period a yields a much smaller ratio of $\sigma_{yy}^b(a/3)/\sigma_{yy}^b(a)$ than is experimentally observed.

In conclusion, we have related the new magnetoresistance oscillations to oscillations of the width of Landau bands created by an artificial 1D superlattice potential. This causes a band conductivity that oscillates with period $2R_c/a$ and may be taken as a direct measure of the effective superlattice potential.

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