Commensurability oscillations and positive magnetoresistance in two-subband quasi-two-dimensional electron system with periodic lateral modulation

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Two-subband magnetotransport of quasi-two-dimensional electron gas in a single quantum well with periodic lateral modulation of electrostatic potential has been studied. In the system under study except Shubnikov–de Haas oscillations, magnetointersubband oscillations and positive magnetoresistance additionally the two series of commensurability oscillations have been observed. Frequencies of this oscillations correspond to commensurability oscillations in two filled subbands of dimensional quantization. Combined analysis of these two series of commensurability oscillations and positive magnetoresistance gives possibility to define mobilities and values of 1D periodic potential modulation for each subband.

Keywords: two-subband electron system, 1D potential modulation, commensurability oscillations of magnetoresistance.

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Commensurability oscillations (CO) of magnetoresistance (MR) constitute a well-known magnetotransport effect occurring in a two-dimensional (2D) electronic system with a one-dimensional (1D) periodic modulation of the electrostatic potential, i. e. 1D lateral superlattice (LSL) [1]. CO are most pronounced in MR measured in the direction of 1D lateral potential modulation: $V(x) = V_0 \cos(2\pi x/a)$, where V_0 — modulation amplitude, a — period. The position of the CO minima on the dependence of the resistance ρ_{xx} on the external magnetic field B perpendicular to the plane of the 2D electronic system is given by the following ralation [2–4]

$$2R_c/a = (i - 1/4), \quad (1)$$

where $R_c = \hbar k_F/eB$ — cyclotron radius, $k_F = (2\pi n)^{1/2}$ — Fermi wave vector, n — density of 2D electron gas, i — positive integer.

The occurrence of CO in 1D LSL in the framework of the quasi-classical model is explained by the resonance between the rotational motion of electrons in an orbit with a diameter of $2R_c$ and the oscillating drift of the center of the orbit induced by the potential $V(x)$ [4]. At the same time, within the framework of quantum mechanical consideration, periodic modulation of the potential $V(x)$ results in the formation of Landau bands in a 2D electronic system, the width of which periodically changes depending on $1/B$. The change of the width of the Landau bands, and the change of the band conductivity σ_{yy} with it, is the quantum mechanical cause of CO [2,3,5,6]. CO occur not only in single-subband 1D LSL, but also in two-subband one [7,8]. Two series of CO occur in 1D LSL with two filled subbands with the following frequencies: $f_{\mathrm{co}j} = 2\hbar k_{\mathrm{F}j}/ea$, where $k_{\mathrm{F}j} = (2\pi n_j)^{1/2}$, and n_j — electron density in j-th subband.

The conductivity of a quasi-two-dimensional electron gas σ_{yy} is the sum of the conductivities in the filled subbands E_j, $\sigma_{yy} = \sum_j \sigma_{yy}^{(j)}$ [9]. Accordingly, the oscillating component of the conductivity of the two-subband 1D LSL $\delta\sigma_{yy} \equiv \sigma_{\mathrm{co}}$ under the conditions $\mu_j B \gg 1$ and $V_{0j}/E_{\mathrm{F}j} \ll 1$ can be expressed by the sum of the oscillating components $\delta\sigma_{yy}^{(j)} \equiv \sigma_{\mathrm{co}j}$ in the subbands, $\delta\sigma_{yy} = \sum_j \delta\sigma_{yy}^{(j)}$ [5.10]:

$$\delta\sigma_{yy} = \sum_j (\pi\hbar n_j^2 \eta_j^2 \mu_j / a k_{\mathrm{F}j} B) A(T/T_{aj}) A(\pi/\omega_c \tau_{\mathrm{co}j}) \times \sin(2\pi f_{\mathrm{co}j}/B), \quad (2)$$

where for j-th subband $\eta_j = V_{0j}/E_{\mathrm{F}j}$ — the magnitude of the relative potential modulation, $E_{\mathrm{F}j}$ — Fermi energy, μ_j — electron mobility, $A(T/T_{aj})$ — CO temperature suppression factor, $T_{aj} = (\hbar\omega_c/k_{\mathrm{B}})(a k_{\mathrm{F}j}/4\pi^2)$, $A(\pi/\omega_c \tau_{\mathrm{co}j})$ — CO collision damping factor, $\omega_c = eB/m^*$ — cyclotron frequency, m^* — effective electron mass, $\tau_{\mathrm{co}j}$ — scattering time characterizing CO suppression with the decrease of ω_c. Since at $\mu_j B \gg 1$ the conductivity is $\sigma_{yy} \approx \rho_{xx}/\rho_{xy}^2$, so the oscillating component of resistivity $\delta\rho_{xx} \equiv \rho_{\mathrm{CO}}$ will be expressed as follows:

$$\delta\rho_{xx} = [B/e(n_1 + n_2)]^2 \delta\sigma_{yy}. \quad (3)$$

There are four fitting values in formulae (2) and (3) for each subband E_j: n_j, μ_j, η_j and $\tau_{\mathrm{co}j}$. The experimental dependence of $\rho_{\mathrm{co}}(1/B)$ makes it possible to determine n_j from the value of $f_{\mathrm{co}j}$, and the values of $\tau_{\mathrm{co}j}$ — from the slope of the dependence of the logarithm of the amplitude of CO on $1/B$ [7]. Therefore, the formule (2) and (3) allow us to find from the experiment only the values of the products $\eta_j^2 \mu_j$.

The values μ_j can be extracted from the analysis of the quasi-classical positive MR in a two-subband system [11,12]:

$$\rho_{sc} = \rho_0 \left[1 + \frac{r(n_1 n_2 \mu_1 \mu_2 / n_s^2)(\mu_1 - \mu_2)^2 B^2}{\mu^2 + r^2 \mu_1^2 \mu_2^2 B^2} \right], \qquad (4)$$

where $\rho_0 = \rho_{xx}(B = 0)$, $n_s = n_1 + n_2$, r — a dimensionless parameter taking into account the intersubband scattering, and $\mu = 1/en_s\rho_0$. The quasi-classical positive MR, due to the difference in mobility in the subbands, should also be manifested in the two-subband 1D LSL. The authors are not aware of studies aimed at finding μ_j and η_j from dependences $\rho_{\mathrm{sc}}(B)$ and $\rho_{\mathrm{co}}(B)$ in two-subband 1D LSL. This paper is devoted to an attempt to fill this gap.

A low-temperature magnetotransport was studied in this paper in a high-mobility two-subband electronic system with one-dimensional periodic potential modulation based on a selectively doped GaAs/AlAs heterostructure. The initial heterostructure was a single GaAs quantum well with a width of 26 nm with AlAs/GaAs short-period superlattice barriers [13,14]. The presence of charge carriers in the quantum well was provided by remote Si δ-doping. Single Si δ-doped layers were located on both sides of the GaAs quantum well at a distance of 29.4 nm from its boundaries. The distance from the center of the quantum well to the upper surface of the structure was 117.7 nm. The heterostructure was grown using the molecular beam epitaxy method on a (100) GaA-substrate.

The studies were carried out on bridges with a width of 50 microns and a length of 100 microns. The bridges were fabricated using optical photolithography and liquid etching. The insert to Figure 1, *a* shows a simplified geometry of the sample. The sample consists of two Hall bridges with a one-dimensional lateral superlattice with a period *a* equal to 200 nm formed on one of the bridges. The LSL comprised a set of metal strips with a length of 60 μm and a width of $\sim a/2$, which were produced using electron beam lithography and the method of „explosion“ of a two-layer Ti/Au metal film. The thickness of the Au layer was 40 nm, and the thickness of the Ti layer was 5 nm. Another bridge was used to control electron density and mobility in an unmodulated two-subband system.

The experiments were conducted at a temperature of $T = 4.2$ K in magnetic fields of $B < 2$ T. The resistance of the samples was measured at alternating current frequency (0.3−1) kHz, the value of which did not exceed 10^{-6} A. In the initial heterostructure, the Hall concentration and electron mobility were $n_{\mathrm{H}} \sim 8.3 \cdot 10^{15}\,\mathrm{m}^{-2}$ and $\mu \sim 110\,\mathrm{m}^2/(\mathrm{v \cdot s})$, respectively. A slight potential modulation occurred in the fabricated 1D LSL without application of a gate voltage V_g to metal strips. One of the reasons for this modulation is the elastic mechanical stresses arising between the metal strips and the adjacent region of the selectively doped GaAs/AlAs heterostructure [15]. The negative voltage V_g applied to the metal strips increased the amplitude of the periodic 1D lateral modulation, and also resulted in a decrease of $n_{\mathrm{H}} \approx n_s$ and μ.

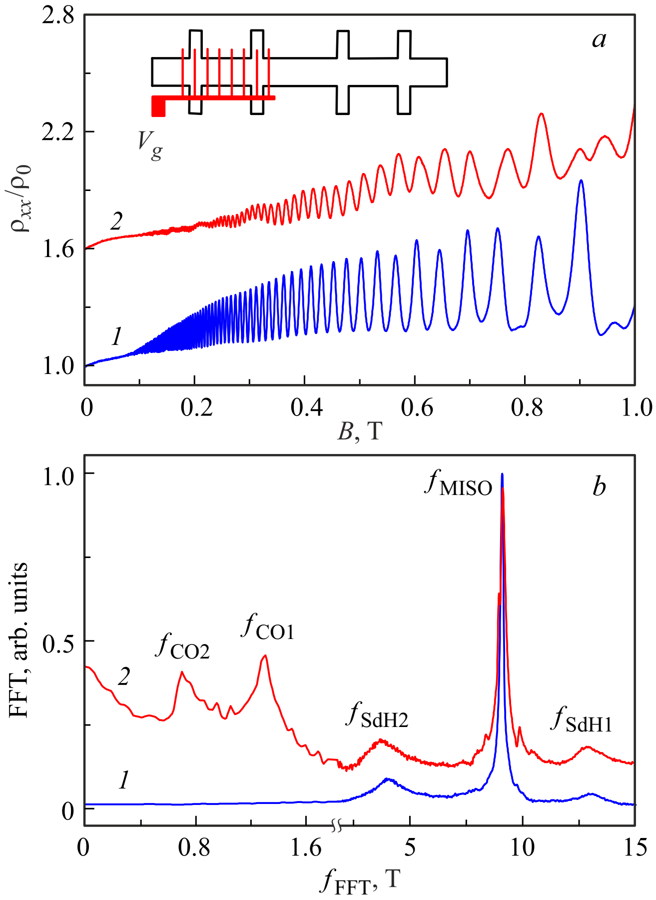

Figure 1. *a* — experimental dependences ρ_{xx}/ρ_0 on B at $T = 4.2$ K: *1* — control bridge; *2* — 1D LSL, $a = 200$ nm, $V_g = -1$ V. The curve *2* is shifted up by 0.6 for clarity. The insert shows a simplified diagram of the sample, on one part of which 1D LSL is formed. *b* — Fourier spectra of dependences ρ_{xx}/ρ_0 from $1/B$ at $T = 4.2$ K: *1* — control bridge; *2* — 1D LSL, $a = 200$ nm, $V_g = -1$ V. The curve *2* for clarity along the axis *y* is multiplied by 3 and shifted up by 0.1.

Figure 1, *a* shows the dependences of ρ_{xx}/ρ_0 on B, measured on the control bridge and on 1D LSL. Only magneto-intersubband (MIS) oscillations [8] are observed on the control bridge, in the range of B from 0.1 to 0.5 T, which in the fields $B > 0.5$ T coexist with Shubnikov–de Haas oscillations (SdH). It can be seen that the amplitude of the MIS oscillations in 1D LSL is significantly less than on the control bridge. The observed suppression of MIS oscillations in 1D LSL is attributable to the formation of Landau bands [16,17]. Three frequencies appear in the Fourier spectrum of the dependence of ρ_{xx}/ρ_0 on $1/B$ for the control bridge (Figure 1, *b*). Two of these frequencies correspond to the frequencies of SdH oscillations in the subbands (f_{SdH1} and f_{SdH2}), and the third frequency corresponds to MIS oscillations ($f_{\mathrm{MISO}} = f_{\mathrm{SdH1}} - f_{\mathrm{SdH2}}$). The frequencies of the SdH oscillations are determined by the relation $f_{\mathrm{SdHj}} = n_j h/2e$, which allows determining n_j in the subbands. Two more frequencies ($f_{\mathrm{co}j}$) are observed in the Fourier spectrum for 1D LSL, in addition to the frequencies f_{SdHj} and f_{MISO}, which correspond to the CO frequencies in subbands.

Figure 2, *a* shows the experimental dependence $\rho_{xx}(B)$ for a two-subband 1D LSL with a period of $a = 200$ nm at $V_g = -1.42$ V. CO co-existing with MIS oscillations are observed on this dependence. CO and MIS oscillations are manifested in magnetic fields of $B > 0.1$ T against a background of positive MR (monotonic component). The dependence $\rho_{\mathrm{mon}}(B)$ in the studied 1D LSL is qualitatively similar to the dependence of positive MR in the unmodulaed two-subband electronic system [14]. It is logical to assume that the dependence $\rho_{\mathrm{mon}}(B)$ for 1D LSL, like in an unmodulated system in weak magnetic fields, is attributable to the mobility difference in the subbands, taking into account the intersubband electron scattering [11,12], and it is attributable to quantum positive MR in strong magnetic fields [18,19]. The calculation of the dependence $\rho_{sc}(B)$ shows that $\rho_{\mathrm{mon}}(B)$ is described by the formula (4) only in the area $B < 0.1$ T. The density values $n_{\mathrm{SdH}j} = (2e/h)f_{\mathrm{SdH}j}$ and the mobility value $\mu = 1/en_s\rho_0$ were used in the calculation. The obtained value of the parameter $r = 0.35$, which takes into account the intensity of intersubband scattering, indicates that μ_j are determined not only by electron scattering inside each subband E_j, but also by intersubband scattering.

The dependence $\rho_{\mathrm{co}}(1/B)$ obtained by Fourier smoothing of MIS oscillations on the dependence of the difference $(\rho_{xx} - \rho_{\mathrm{mon}})$ on $1/B$ is shown by a solid line on Figure 2, *b*, and the dependence $\rho_{\mathrm{co}}(1/B)$, calculated using the formulae (2) and (3) is shown by circles.The values $f_{\mathrm{co}j}$, $\tau_{\mathrm{co}j}$ and η_j were the fitting parameters. The concentrations $n_{\mathrm{co}j} = (eaf_{\mathrm{co}j}/2\hbar)^2/2\pi$: $n_{\mathrm{co1}} \approx 6.3 \cdot 10^{15}\,\mathrm{m}^{-2}$ and $n_{\mathrm{co2}} \approx 1.55 \cdot 10^{15}\,\mathrm{m}^{-2}$ correspond to the values $f_{\mathrm{co1}} \approx 1.31$ T and $f_{\mathrm{co2}} \approx 0.65$ T obtained from the fitting. The electron densities of $n_{\mathrm{co}j}$ differ from $n_{\mathrm{SdH}j}$ by less than 5%, which corresponds to our experimental accuracy. The values of the ratios $(m^*/e)\mu_j/\tau_{\mathrm{co}j}$ for the first and second subbands were 7.44 and 12.6, respectively. Such values $(m^*/e)\mu_j/\tau_{\mathrm{co}j}$ indicate that $\tau_{\mathrm{co}j}$ in the studied system, as well as τ_{co} in single-subband 1D LSL [10], are determined mainly by small-angle scattering [13].

We obtained the following values for relative modulation values $\eta_j = V_{0j}/E_{\mathrm{F}j}$: $\eta_1 \approx 0.006$ and $\eta_2 \approx 0.045$ using the values $n_j = n_{\mathrm{SdH}j}$ and the values μ_j extracted from the comparison $\rho_{\mathrm{sc}}(B)$ and $\rho_{\mathrm{mon}}(B)$. These values η_j correspond to the values of the amplitudes of lateral potential modulation in the subbands V_{0j} : $V_{01} \approx 0.13$ meV and $V_{02} \approx 0.26$ meV. The potential of the 1D lateral superlattice causes a corresponding lateral modulation of the quasi-two-dimensional gas density. The relative modulation of the potential in the subband is equal to the relative lateral modulation of the density n_j: $\eta_j = V_{0j}/E_{\mathrm{F}j} = \delta n_{0j}/n_j$ when the acting potential 1D LSL has only one spatial harmonic [3].

In accordance with this the density modulation amplitudes δn_{0j} in the studied two-subband 1D LSL for $V_g = -1.42$ V amount to $\delta n_{01} \approx 3.7 \cdot 10^{13}\,\mathrm{m}^{-2}$ and $\delta n_{02} \approx 7.3 \cdot 10^{13}\,\mathrm{m}^{-2}$. The change of density in the subband n_j with a small change of gate voltage V_g is $\Delta n_j = (dn_j/dV_g)\Delta V_g$. In our case, the ratio of the values of density modulation $\delta n_{02}/\delta n_{01} \approx (dn_2/dV_g)/(dn_1/dV_g)$, where dn_j/dV_g — „slope“ of the dependences $n_j(V_g)$ for the original unmodulated heterostructure in the domain $V_g < -1$ V [14]. This ratio indicates that in the studied two-subband 1D LSL, the lateral modulation for $V_g = -1.42$ V is set by the gate voltage.

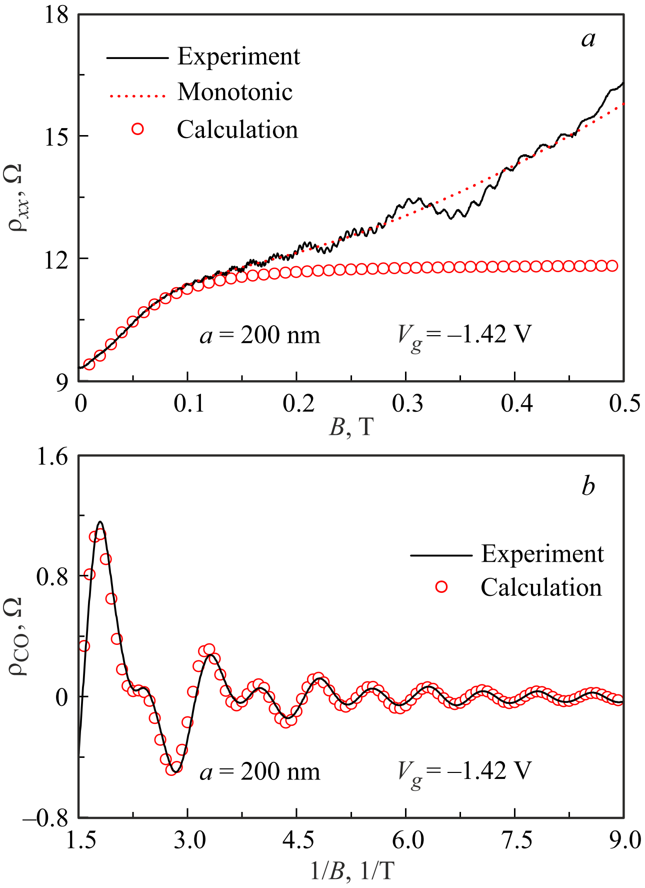

Figure 2. *a* — experimental, monotonic and calculated dependences of ρ_{xx} on B for 1D LSL at $T = 4.2$ K: $a = 200$ nm; $V_g = -1.42$ V; $\rho_0 \approx 9.32$ Ohm; $n_1 \approx 6.19 \cdot 10^{15}\,\mathrm{m}^{-2}$; $n_2 \approx 1.62 \cdot 10^{15}\,\mathrm{m}^{-2}$; $\mu \approx 85.7\,\mathrm{m}^2/(\mathrm{V}\cdot\mathrm{s})$. Calculation using the formula (4): $n_1 = 6.19 \cdot 10^{15}\,\mathrm{m}^{-2}$; $n_2 = 1.62 \cdot 10^{15}\,\mathrm{m}^{-2}$; $\mu = 85.7\,\mathrm{m}^2/(\mathrm{V}\cdot\mathrm{s})$; $\mu_1 = 96.2\,\mathrm{m}^2/(\mathrm{V}\cdot\mathrm{s})$; $\mu_2 = 45.8\,\mathrm{m}^2/(\mathrm{V}\cdot\mathrm{s})$; $r = 0.35$. *b* — experimental and calculated dependences ρ_{co} on $1/B$ for 1D LSL. Calculation using formulae (2) and (3): $T = 4.2$ K; $a = 200$ nm; $n_1 = 6.19 \cdot 10^{15}\,\mathrm{m}^{-2}$; $n_2 = 1.62 \cdot 10^{15}\,\mathrm{m}^{-2}$; $\mu_1 = 96.2\,\mathrm{m}^2/(\mathrm{V}\cdot\mathrm{s})$; $\mu_2 = 45.8\,\mathrm{m}^2/(\mathrm{V}\cdot\mathrm{s})$; $\eta_1 = 0.006$; $\eta_2 = 0.045$; $\tau_{\mathrm{co1}} = 5$ ps; $\tau_{\mathrm{co2}} = 1.4$ ps; $f_{\mathrm{co1}} = 1.31$ T; $f_{\mathrm{co2}} = 0.65$ T.

Thus, a low-temperature magnetotransport of quasi-two-dimensional Fermi electron gas in two-subband 1D LSL fabricated on the basis of a selectively doped single GaAs quantum well with short-period AlAs/GaAs superlattice barriers was studied. Two series of CO, each associated with its own subband, coexist with MIS oscillations in the studied

1D LSL and are observed against the background of positive MR. It is shown that a joint analysis of the experimental magnetic field dependences of positive MR and two series of CO within the framework of known theoretical models makes it possible to estimate the amplitudes of 1D lateral periodic potential modulation separately for each of the filled subbands of dimensional quantization.

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Conflict of interest

The authors declare that they have no conflict of interest.

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